MONTREAL PROTOCOL

ON SUBSTANCES THAT DEPLETE

THE OZONE LAYER

UNEP

2002 REPORT OF THE

METHYL BROMIDE

TECHNICAL OPTIONS COMMITTEE

2002 Assessment

Montreal Protocol on Substances that Deplete the Ozone Layer

United Nations Environment Programme (UNEP)
2002 Report of the Methyl Bromide Technical Options Committee

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Dedication

This 2002 MBTOC Assessment Report is dedicated to our good friend and colleague Dr Miguel Costilla (Investigador, Seccion Zoologia, Estacion Experimental Agro-Industrial Obispo Colombres, Argentina) who passed away suddenly in 2001. He will be remembered by his MBTOC colleagues for his friendship, hard work and dedication toward finding alternatives to methyl bromide.

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Executive Summary

The Methyl Bromide Technical Options Committee

The Methyl Bromide Technical Options Committee (MBTOC) was established by the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer to identify existing and potential alternatives to methyl bromide (MB). This Committee, in particular, addresses the technical feasibility of chemical and non-chemical alternatives for the current uses of MB, apart from its use as a chemical feedstock.

MBTOC reports to the Technology and Economic Assessment Panel (TEAP) which advises the Parties on scientific, technical and economic matters related to the control of ozone depleting substances and their alternatives. MBTOC members have expertise in the uses of MB and its alternatives. At December 2002 MBTOC had 34 members; 10 (29%) from developing and 24 from developed countries and coming from 9 Article 5(1) and 10 non-Article 5(1) countries respectively.

Mandate and Report Structure

Under Decision XI/17, taken at the ninth Meeting of the Parties to the Protocol in 1997, the Parties requested the Assessment Panels, to update their 1998 Assessment reports and submit them to the Secretariat for consideration by the Open-Ended Working Group and by the fifteenth Meeting of the Parties in 2003.

This MBTOC 2002 Assessment reports on MB usage; the quantities produced and consumed; existing and potential alternative treatments for uses as a soil fumigant; as a fumigant of durable commodities and structures; and as a fumigant for quarantine and pre-shipment (QPS).

In addition, the report provides sections in response to Decision IX/5(1e) and also on methods for reducing MB emissions. Decision IX/5(1e) notes that, in the light of an assessment to be made by the Technology and Economic Assessment Panel, the Meeting of the Parties shall decide in 2003 on further specific interim MB reductions in Article 5(1) Parties for the period beyond 2005. To aid this assessment, information is provided on the extent to which alternatives have been tested and evaluated in Article 5(1) countries, and the results of demonstration projects which examined efficacy with respect to target pests, ease of application, availability, relevance to climatic conditions, soils and cropping patterns found in Article 5(1) regions.

General Features of Methyl Bromide

MB is a fumigant that has been used commercially for more than 50 years to control pests such as fungi, bacteria, soil-borne viruses, insects, mites, nematodes and rodents. It has sufficient phytotoxicity to control many weeds and seeds in soils. MB is used mostly for soil fumigation, a lesser amount is used for disinfestation of durable and perishable commodities and some is used for disinfestation of buildings, ships and aircraft, and other miscellaneous uses. It has well established uses for quarantine and pre-shipment treatment of a diverse range of pests and diseases.

It has features that make it a versatile material with a wide range of potential applications. In particular, it is a gas that is quite penetrative and usually effective over a broad range of temperatures. Its action is usually sufficiently fast and it airs rapidly enough from treated systems to cause relatively little disruption to commerce or crop production.

Methyl bromide was listed under the Montreal Protocol as an ozone depleting substance in 1992. Control schedules leading to phaseout were agreed in 1995 and 1997. There are a number of concerns apart from ozone depletion that have also led countries to impose restrictions on its use. These concerns include residues in food, toxicity to humans and associated operator safety and public health, and detrimental effects on soil biodiversity. In some countries, pollution of surface and ground water by MB and its derived bromide ion are also concerns.

Production and Consumption

The latest year for which production and consumption estimates are available is 2000. MBTOC used primarily the data reported by Parties to the Ozone Secretariat to estimate total production and consumption. Data gaps were filled by using data from the previous reported year.

MB production trends

Global MB production for all uses (including QPS and feedstock) in 1998, as reported to the Ozone Secretariat, was about 75,200 metric tonnes. Ozone Secretariat reports indicate that global MB production for controlled uses (i.e. excluding QPS and feedstock) was at least 62,750 tonnes in 1998. This data set is not complete and other sources indicate that it was somewhat higher. Production for controlled uses was reported to be at least 49,560 tonnes in 1999 and about 46,050 tonnes in 2000. The reductions reflect primarily the production controls implemented in non-Article 5(1) countries. Most MB production occurs in the USA and Israel.

MB consumption trends

Parties reported MB consumption of about 60,200 tonnes in 1998 (excluding QPS), although some sources indicate higher consumption. On the basis mainly of Ozone Secretariat data, MBTOC estimated that, for controlled uses, at least 49,170 tonnes MB was consumed in 1999 and at least 45,360 tonnes in 2000. Although the data set is incomplete, the data at country level indicates MB consumption has been reduced in non-Article 5(1) counties in line with the Protocol requirements.

Controlled MB consumption in Article 5(1) countries rose from about 8,460 tonnes in 1991 to about 17,600 tonnes in 1998, representing an increase of 15% per year on average. However, since 1998 the consumption has decreased at an average rate of about 5% per year (1998-2000). Based on Ozone Secretariat data reported so far, MBTOC estimated the total Article 5(1) MB consumption to be around 16,440 tonnes in 2000. Between 1998 and 2000, national MB consumption fell by more than 20% in some Article 5(1) countries, but increased significantly in others.

As at December 2002, the Multilateral Fund had approved 38 MB phaseout projects that are designed to eliminate almost 8,000 tonnes of MB in Article 5(1) countries. The projects are scheduled to phase out about 75% of this before 2006. The speed of planned MB reductions depends on a variety of factors, such as the initial consumption level, MB uses/crops and national policies. In the 15 countries that plan full phaseout , MB is scheduled to be reduced at an average annual rate of about 22.5% per year, in a total of 4.4 years on average (range 3-6 years). This includes countries that are small, medium and large MB consumers.

A number of additional MB phaseout projects are under development by the MLF and other organisations. The existing and anticipated projects are due to lead to the phaseout of about 10,000 tonnes MB before about 2007, eliminating more than 50% of the peak consumption in Article 5(1) regions.

A MBTOC survey of ozone offices and national experts in 2001/2 provided information on the breakdown of MB uses in major MB-consuming countries. In 2000, an estimated 67% was used for soil and 33% for commodities/structures, including QPS.

Methyl bromide emissions

Under current usage patterns, the proportions of applied MB eventually emitted to the atmosphere are estimated by MBTOC to be 40 - 87%, 85 - 98%, 69 - 79% and 90 - 98% of applied dosage for soil, perishable commodities, durable commodities and structural treatments respectively. These figures, weighted for proportion of use and particular treatments, correspond to a range of 50 - 87% overall emission from agricultural and related uses, with a best estimate of overall emissions of 73%, or 40,515 metric tonnes based on production of 55,500 tonnes in 2000.

Methyl Bromide Control Measures

The current control measures, agreed by the Parties at their ninth Meeting in Montreal in September 1997, can be paraphrased as:

For non-Article 5(1) Parties operating under the Protocol (developed countries) a 25% cut in production and consumption, based on 1991 levels, from 1 January 1999, a 50% cut from 1 January 2001, a 70% cut from 1 January 2003 and phase out by 1 January 2005 with provision for exemptions for any critical uses. A freeze on MB production and consumption based on 1991 levels already applies from 1 January 1995.

For Parties operating under Article 5(1) of the Protocol (developing countries) a 20% cut in production and consumption, based on the average in 1995-98, from 1 January 2005 and phase out by 1 January 2015 with exemptions for any critical uses. There is also a freeze on MB production and consumption based on 1995-98 levels from 1 January 2002 which was agreed at the ninth Meeting of the Parties in 1997.

The Protocol provides an exemption under Article 2H para. 6 for all Parties for the amounts of MB used for QPS purposes. Additionally, certain uses of MB may be allowed exemptions from phaseout after 2005 if they are deemed to meet the criteria for 'critical uses' defined by the Parties.

Alternatives to Methyl Bromide

Definition of an alternative

MBTOC defined 'alternatives' as those non-chemical or chemical treatments and/or procedures that are technically feasible for controlling pests, thus avoiding or replacing the use of MB. `Existing alternatives' are those in present or past use in some regions. `Potential alternatives´ are those in the process of investigation or development.

MBTOC assumed that an alternative demonstrated in one region of the world would be technically applicable in another unless there were obvious constraints to the contrary e.g., a very different climate or pest complex.

MBTOC is not required in its terms of reference to conduct economic studies on MB and alternatives. Additionally, it was recognised that regulatory requirements, environmental issues and social constraints may make an alternative unavailable in a specific country or region. MBTOC did not omit alternatives from consideration on such grounds.

Availability of alternatives

MBTOC could find no existing technical alternatives for about 3,200 tonnes of MB per annum used for non-QPS treatments. Based on this relatively small consumption of MB and bearing in mind the above definition of an alternative, there are existing alternatives for more than 93% of current consumption of MB, excluding QPS. Significant effort must now be undertaken to transfer, register and implement these alternatives and to optimise their use.

While an alternative may be technically appropriate as an MB replacement for a given situation, it may not be available in practice. For example, registration is a major constraint affecting the availability of certain alternatives, particularly novel chemicals or chemicals applied to new uses. In many countries, the pesticide registration process requires the generation of a substantial amount of health and safety data. The potential health and environmental risks must be assessed thoroughly and appropriate mitigation controls put in place before an alternative can be registered. Overall, the registration and approval process is often costly and protracted, with the outcome uncertain from the point of view of the potential registrants. In addition, the market size for a particular MB application may be too small to justify the commercial risk and investment involved. These problems are particularly noted where use on foodstuffs is involved and registration costs are high, such as with MB alternatives for many postharvest applications, including QPS. However, some countries have registered some alternatives in recent years and some large MB-volume consuming countries are currently considering registration for additional alternatives. There is the possibility that further registrations for use will be completed prior to 2005 phaseout in some non-Article 5(1) countries.

Alternatives for soil treatments

The reduction in consumption of MB for soil fumigation has been the major contributor to the overall reduction in global consumption of MB as most non-Article 5(1) countries have met or exceeded the 50% reduction schedules for soil use agreed under the Montreal Protocol.

Since the 1998 MBTOC Report, clearer trends have developed in the adoption of alternatives to replace MB as a preplant soil fumigant. These include alternatives that either provide broad-spectrum control of pests, diseases and weeds (e.g. chemicals and their combinations, steam and solarisation) or cultural practices which avoid the need for MB.

MB used alone, or in mixtures with chloropicrin, is still being used for preplant soil disinfestation to manage a similar range of crop/pathogen complexes to those that were recorded in the 1998 Report. The major crops for which MB is still widely used in some regions include; cucurbits, pepper, tomatoes, perennial fruit and vine crops, cut flowers and bulbs, strawberry fruit and turf. MB may also be used in the production of propagation material for forests, fruit and vine crops, strawberries, ornamental trees and tobacco.

Although significant progress in alternatives to MB has been made since the 1998 report, MBTOC recognises that the complexity of soil pathogen and weed problems in different countries and the diversity of environments in agriculture require the continued development and adaptation of non-chemical and chemical methods. Further investment in research and technology transfer will be necessary to implement alternative pest management systems effectively in all countries.

Feasibility and adoption of alternatives to MB may be affected by local availability, registration status, market requirements, costs, labour inputs and efficacy against pests, disease and weed complexes and, in some cases, by reduction of crop yield or quality. Alternatives need to demonstrate sufficient efficacy and yields over several seasons, before confidence is obtained for their commercial use.

To date, reductions in the amount of MB used for soil disinfestation have been achieved mainly by the adoption of transitional strategies and to a lesser extent by adoption of alternatives in non-Article 5(1) countries. In Article 5(1) countries reductions have been made largely by adopting alternatives.

The main transitional strategies used include:

MB/chloropicrin mixtures with lower concentrations of MB, the use of lower doses of MB and/or to a lesser extent the adoption of barrier films.

Less frequent fumigation.

The major alternatives adopted to offset the use of MB include:

Fumigants and other chemical pesticides applied alone or as mixtures. 1,3-dichloropropene (1,3-D) and mixtures of 1,3-dichloropropene/chloropicrin (1,3-D/PIC) are the most common fumigant alternatives being adopted, followed by metham sodium, dazomet and chloropicrin used alone. Combinations of 1,3-D, PIC, metham and dazomet, with or without additional herbicides and fungicides, or other non-chemical alternatives have been proven as effective as MB in research trials, but need further commercial validation.

Solarisation, alone or combined with biofumigation, has gained wider acceptance to replace MB in areas with hot climates and where it suits the cropping season and the pest and disease complex.

Steaming is being adopted for high value crops grown in protected agriculture e.g. greenhouses, particularly when quick turn around times are required or where fumigant use is impractical.

Soilless culture is a rapidly expanding cropping practice, primarily for protected agriculture, which has offset the need for MB, especially in some floricultural crops, vegetables and seedling production. In particular, flotation systems, based on soilless substrates and hydroponics, have replaced over 80% of MB for tobacco seedling production worldwide. The adoption of this technique is currently expanding into cut flower and some vegetable production.

Grafting, resistant rootstocks and resistant varieties are commonly used practices to control soilborne diseases in vegetables, flowers and fruit trees and are being more commonly adopted as part of an integrated pest control system. Although grafting is used widely to control specific diseases of many crops for which methyl bromide is still used, MBTOC did not have the data to determine the extent to which these practices have replaced MB for soil disinfestation.

In addition to the above specific technologies, integrated pest management (IPM) strategies have also been developed for control of pests, diseases and weeds using combinations of a range of other chemical and non-chemical alternatives. IPM strategies have been developed for specific pests, climatic regions and soil types but further development is required in many countries, before IPM can be expected to provide the broad spectrum control that is presently achieved by MB.

Potential alternatives include:

> Methyl iodide, propargyl bromide and sodium azide which have each been demonstrated in research trials to be effective as direct replacements for MB in some cropping systems where MB is currently used.
>
> Biological control agents, organic amendments, and incorporation of green manures into the soil, have been subjected to a considerable amount of research and have a role in integrated systems. Significant advances in the use of these techniques have been accomplished for the control of soilborne diseases in horticultural crops. There are specific crop/pest combinations where green manures have successfully replaced MB when combined with other methods, particularly solarisation.

MBTOC estimates that the reductions in MB consumption from 1991 baseline consumption for non-Article 5(1) Parties for soil fumigation result from mainly from transitional strategies (about 30% of the reduction), use of alternative fumigants and chemical treatments (10%) and use of soilless systems (5%). Other measures, steaming and solarisation, account for less than 1% of the present reduction in use, though they are important as alternatives in some particular situations.

Projects in Article 5(1) countries have demonstrated that a similar range of alternatives to those in non Article 5(1) countries can be successfully adopted. Costs and different resource availability can lead to preference for different alternatives in Article 5(1) compared to non-Article 5(1) countries.

Research has not yet determined conclusively that MB can be replaced in certain production systems to give similar outcomes, notably certain perennial crops and some other replant situations, and production of certain propagation materials meeting legislated requirements for pest-free status. Also, several diseases of certain crops are proving difficult to control, including root rot of ginseng in China and a soilborne virus (cucumber green mottle mosaic virus) in Japan. Since the 1998 Report, MBTOC has revised its estimate of the annual quantity of MB required for these difficult situations worldwide from 2500 to 3000 tonnes.

Alternatives for treatment of durables, wood products and structures (non-QPS)

Durables are commodities with a low moisture content that, in the absence of pest attack, can be safely stored for long periods. They include foods such as grains, dried fruits, cocoa beans, animal feeds and non-foods such as wood products, wool, cotton, and tobacco. Wood products include artefacts and other items of historical significance; unsawn timber, timber products and bambooware; wooden packaging materials and manufactured articles. All these commodities may sometimes be treated at present with MB for control of insects and other pests.

Structures include entire buildings and portions thereof, including mills, food production and storage facilities, and transport vehicles, including ships, aircraft, freight containers and other vehicles, These all may all sometimes be treated with MB to control stored product or wood destroying insects, rodents and other pests.

It is estimated that approximately 15% of the annual world non-feedstock usage of MB is for the disinfestation of durable commodities and about 2.5% for structures.

MBTOC estimates that 5-10% of controlled MB usage for durables has been replaced since 1998.

There are several existing alternatives to MB for disinfestation of durable commodities and structures, though MB may be used in preference because of traditional practice, perceived reliability or speed of action, or for contractual reasons. The principal alternatives in use for durables are phosphine, heat, cold and contact pesticides; for wood products, they are sulphuryl fluoride, chemical wood preservatives, and heat; for structures, they include sulphuryl fluoride, and heat. The choice of appropriate alternatives is dependent on the commodity or structure to be treated, the situation in which the treatment is required, the accepted level of efficacy, the desired speed of action required and the cost, and registration status of alternatives.

There are a small number of current non-QPS uses of MB for which MBTOC did not identify any existing alternatives. For durables, these are: disinfestation of fresh chestnuts, disinfestation of fresh walnuts for immediate sale, stabilisation and disinfestation of high moisture fresh dates, elimination of seed-borne nematodes from alfalfa and some other seeds for planting, and control of organophosphate-resistant mites in traditional cheese stores. In treatment of mills and food processing facilities where IPM systems have not proved adequate, or are very difficult to implement, and where heat treatment is not feasible, it may be necessary to resort to occasional use of MB. In addition there is no recognised alternative for control of fungi in historical structures. The total requirement of MB for these uses is unlikely to exceed 150 tonnes per annum.

Phosphine is the only available in-kind alternative extensively used on durables. Cylinder-based formulations are now available in several countries. Phosphine has the potential to act as a direct substitute for MB in many situations but can also act as a component of an IPM process to avoid MB use. Its action against pests is much slower than MB, particularly at low temperatures. Insect populations are capable of developing resistance to phosphine more readily than MB. There are continued concerns over potential corrosion of some metals and electronic components that impact acceptability of phosphine as an MB alternative for some structural fumigations.

There are several other chemicals that may have some potential as alternatives for MB, but the small market size, and consequent poor return for investment for registrants, limits prospects for their availability. This is particularly a problem for durable and QPS treatments, due to the wide variety of commodities involved. In addition fumigants require specialist training to achieve adequate standards of safety and efficacy. Although hydrogen cyanide was once widely used for treatment of structures and durable commodities, its availability and limitations related to health and safety issues inhibit its immediate substitution for current uses of MB in many countries. Ethyl formate, carbon bisulphide, propylene oxide and ethylene oxide have been or are useful in selected situations. Sulphuryl fluoride is used for controlling wood destroying pests in residences, other buildings and wood products and registration is being sought in the US and Europe for commodities. Carbonyl sulphide is under consideration in Australia for registration for use on various durable commodities.

Treatment with controlled atmospheres (CA) based on carbon dioxide or nitrogen offers an alternative to fumigation for insect pest control, but while the growth of fungi is inhibited in the atmosphere, growth resumes after treatment. MB has been replaced in many countries by CA for disinfestation of artefacts. High pressure CO_2 acts even more rapidly than MB and is an alternative for some export situations, though installation costs are relatively high. CA at normal pressure is much slower acting than MB except at elevated temperatures.

Vacuum technologies using low cost plastic enclosures have recently been commercialised. These simple systems provide a means of holding an insecticidal low oxygen atmosphere at low cost, and also they aid the effectiveness of some fumigants.

Where registered for use, synthetic pesticides including contact insecticides and insect growth regulators may provide persistent protection against reinfestation. Dichlorvos where registered, can provide a rapid control of externally feeding insect stages in grain. Contact insecticides are not normally registered for use on processed food commodities or dried fruit, nuts and cocoa beans. Botanical compounds, such as plant powders, extracts and oils have minor and traditional applications as insecticides in Article 5(1) countries.

Physical methods of insect control, including mechanical measures during handling and processing, cold, heat and irradiation treatments, offer further potential as non-chemical alternatives in individual circumstances. Cold treatments are now used on their own in specific situations or, more commonly, as part of IPM systems for stored products and artefacts. Heat treatment technologies are increasingly used for structures and some commodities and match the speed of treatment afforded by MB and other fast-acting fumigants. Heating can also assist other treatments, for example fumigants, controlled atmospheres and inert dusts. Inert dusts such as those based on diatomaceous earth can provide effective pest control in dry grain and as part of an IPM program in structures.

Alternatives evaluated in Article 5(1) countries – Response to Decision IX/5(1e)

Several MB alternatives have been selected in Article 5(1) countries for extensive adoption as part of MB phaseout (investment) projects, following successful demonstration projects, and progress in MB reductions in Article 5(1) regions.

By December 2002 the Multilateral Fund (MLF) had approved a total of 232 MB projects in more than 63 countries. This included 44 demonstration projects for evaluating and customising alternatives, 38 MB investment projects for phasing-out MB and 150 other projects for information exchange, awareness raising, policy development and project preparation. Further MB replacement activities have been funded directly by Article 5(1) countries and/or agricultural producers, bilateral assistance and the Global Environment Facility.

MB phaseout projects approved to December 2002 are scheduled to eliminate major uses of MB in 35 Article 5(1) countries. The projects aim to achieve the widespread commercial adoption of alternatives that were found effective during demonstration projects and/or used in similar climates and conditions in other countries.

Demonstration projects have been carried out in Article 5(1) countries using a wide range of chemical and non-chemical alternatives, in diverse situations, climates, soil types and cropping systems, and for many different types of MB users, ranging from small producers with less than 0.5 ha, to medium and large producers, who produce under low, medium and higher levels of technical sophistication (which does not necessarily correlate with size of operation).

Twenty-nine demonstration projects evaluated and customised alternatives in the soil sector, covering all the MB-using major crops in Article 5(1) regions, (tomato, cucumber, pepper, strawberry fruit, melon, cut flowers, nurseries and tobacco seedbeds). About 16 of the projects (completed and on-going) evaluated alternatives for post-harvest uses of MB, such as on stored grains, pulses, peanuts, seeds and dates.

The completed demonstration projects to date show that for all locations and all crops or situations tested, except control of ginseng root rot and stabilisation of high-moisture fresh dates, one or more of the alternatives have proven comparable to MB in their effectiveness in the control of pests and diseases targeted in the projects in these Article 5(1) countries. In many cases, combined techniques have provided more effective results than individual techniques, particularly when they are part of an integrated pest management (IPM) program.

The results indicate that particular attention needs to be paid to appropriate, effective application methods. Adapting the alternatives to the specific cropping environment and local conditions is essential to success. For example, local materials such as coconut coir and rice hulls have made it possible to adapt substrate systems that would normally have required know- and how technically-demanding materials (e.g. rockwool) not widely available in developing countries. These demonstration projects also showed that the tested alternatives could be introduced into an Article 5(1) country and adapted successfully within 2-3 years, in some cases even including registration of pesticide products.

The main techniques found effective in demonstration projects and/or being implemented in follow-up investment projects for the main MB-using crops/uses are:

Tobacco seedbeds: The soilless float system is an effective MB alternative, applicable to most regions where tobacco is grown. Countries now implementing MB phaseout projects in tobacco have primarily chosen to adopt float systems. Their use is increasing in countries like Brazil, Cuba, Zimbabwe, Argentina, Macedonia and Croatia, and has very good potential in China. In some countries, effective results in tobacco seedbeds were also achieved with dazomet and dazomet + solarisation.

Cut flowers: Steam + IPM, metham sodium, substrates, and dazomet were all identified as effective alternatives to MB in diverse conditions. Countries implementing phaseout projects in the cut-flower sector have chosen to adopt these same treatments. Steam with organic amendments is used commercially in, for example, Colombia. Commercial adoption of substrates in greenhouse flower production is increasing in Colombia, Brazil, Ecuador and many other countries.

Tomato, cucumber, melon, peppers, eggplant and other vegetables: The demonstrations identified solarisation + biofumigation, solarisation + metham sodium or dazomet, and grafting as treatments with effects comparable to MB for the control of soilborne pests and diseases. Examples of commercial use include solarisiation + metham and solarisation + biofumigation in tomato and pepper production in

Uruguay. Solarisation with biofumigation is widely used by tomato and cucumber growers in the Jordan Valley. Use of grafted tomato plants + IPM is now a common practice among farmers in Morocco and is being introduced in Lebanon. Countries who are implementing MB phaseout projects for vegetables/melons have chosen to adopt alternatives such as substrates, grafted plants, direct seeding, solarisation combined with fumigants or organic matter or biofumigation, and steam + biocontrol agents.

Strawberries (fruit production): Demonstrations identified metham sodium, dazomet, solarisation and combinations of these as effective alternatives to MB under Article 5(1) conditions. Solarisation alone or in combination with biofumigation or *Trichoderma* was reported as having high potential for commercial adoption in Turkey. Dazomet + 1,3-D and chloropicrin are being adopted commercially in some CEIT countries. Countries that are implementing MB phaseout projects in the strawberry sector have chosen to adopt alternatives such as solarisation combined with metham sodium or with manure and *Trichoderma*. Biofumigation + 1,3-D and steam have also been selected, the precise combination of techniques depending on the climate, the soil type and target pests, as for all other crops.

Banana and fruit trees: Dazomet has proved an efficient alternative to MB for controlling Moko disease of bananas. This chemical is now widely used commercially in banana plantations (e.g. in Colombia and the Philippines). Countries who are implementing MB phaseout projects for banana plan to adopt combinations of steam, 1,3-D, metham sodium or solarisation. For fruit trees Article 5(1) countries plan to adopt alternative fumigants + selected chemicals for replant problems, and steam or steam + biocontrols for fruit tree nurseries.

Stored products (durables): Many former storage uses of MB in Article 5(1) countries have already been replaced by phosphine, as noted in previous MBTOC reports. In most cases the current choice of alternative treatments lies between phosphine, carbon dioxide, combinations of these gases with raised temperatures and high or low pressures, other modified atmosphere systems, heating, and vacuum-hermetic treatments. While the limited choice at present is strategically undesirable, the range of available alternatives is expected to increase in future. However, the techniques available at present can achieve effective (non-QPS) disinfestation of almost all stored products without recourse to MB.

The completed demonstration projects identified one or more technically effective alternatives to MB for all the stored products tested, except high moisture fresh dates. Projects generally concluded that alternatives should be implemented together with integrated commodity management (IPM) programmes.

The projects found that phosphine was technically effective against target pests in stored wheat, maize, rice, peanuts for seed, spices and dried fruit. The demonstration project in Egypt concluded that phosphine (combined with improved gastightness) is an effective alternative for grains in bag stacks, silos and warehouses. Vacuum-hermetic treatments were found to provide an effective treatment for cocoa beans in Côte d'Ivoire. Modern hermetic storage has been recently adopted commercially in the Philippines for stored grains.

Countries that are implementing MB phaseout projects have chosen to adopt phosphine with integrated commodity management (ICM) for stored wheat, maize and peanuts. For dried fruits they have chosen carbon dioxide with raised temperature.

The projects described above show that substantial progress has been made in the identification of suitable alternatives in Article 5(1) countries. They indicate that it will be technically feasible for Article 5(1) countries to make substantial reductions in MB use. Experience with demonstration and investment projects to date, such as those supported by the Multilateral Fund, indicate that the many technical, climatic, social and economic barriers to MB alternatives can be successfully overcome in diverse Article 5(1) regions and that alternatives can be adopted within a relatively few years. Commercial availability of certain alternatives for application in Article 5(1) countries is of continued concern.

Alternatives to methyl bromide for quarantine and pre-shipment applications (perishables, durable commodities and structures)

Many perishable and durable commodities in trade or storage lose quality and value when they are attacked by pests such as insects, mites and fungi. These commodities may also carry pests and diseases that can be a threat to agriculture, health and the environment. There are a wide variety of QPS measures that can be taken so that any potential losses and risks can be mitigated, including fumigation with methyl bromide (MB) or the use of a range of alternatives to MB.

For quarantine and pre-shipment purposes, MB fumigation is currently a preferred treatment of commodities in trade worldwide, particularly for insect pest control, as it has a well-established, successful reputation amongst plant regulatory authorities. MB may also be approved for QPS treatments of snails, nematodes, other invertebrate pests, some fungi, and vertebrate pests. Mandatory MB treatments may be required if the pest present is of quarantine concern, and particularly if it is difficult to detect but there is a risk it is present. In some cases, MB may be used for devitalisation as well as for disinfestations (e.g. for some cut flower types). Quarantine pests, detected in a country or region previously free of them, can result in considerable cost caused by restriction of exports, eradication measures and implementation of disinfestation treatments if eradication is not achievable.

Article 2H exempts MB used for quarantine and pre-shipment (QPS) treatments from phaseout, while Decision VII/5(c) urges Parties to adopt recapture technology for QPS applications. The European Community is one of the few Parties that has placed conditions additional to those under the Protocol on MB consumed for QPS, including a cap on the amount that can be used and further reporting requirements. Japan has mandated application of coloured labels to the cylinders to differentiate MB used for QPS or non-QPS.

TEAP reported previously that approximately 22% of MB global consumption was used for QPS treatments. As requested by the Parties in Decision XI/13, MBTOC will *inter alia* undertake a survey in 2002 and report in the 2003 on the consumption and use of MB for QPS treatments.

MBTOC categorised thirteen different categories of alternative treatments such as heat, cold and irradiation that are approved by regulatory agencies as QPS treatments in one or more countries for disinfestation of perishable and durable commodities. Only a small proportion of commodities in commercial trade are treated in the export country using these alternatives as most countries have specific requirements for proving the efficacy for each commodity-pest combination. Post-entry alternative treatments used by the importing country are particularly problematical because many alternatives have neither been approved for treating a specific product on arrival, nor are they easy to implement. To solve this problem, development of a range of alternatives is urgently needed to cope with a large and highly varied volume of produce entering via multiple air and sea ports. Such treatments would need to be able to treat perishable commodities quickly to avoid congestion at busy ports and, for perishable commodities, allow the product to be placed on the market within a few hours of receival.

Alternatives to MB for quarantine treatments are difficult to develop and commercialise. The success of any replacement for MB depends on a number of factors that include: proven treatment efficacy; commodity tolerance; equipment design and commercial availability; regulatory approval, often including bilateral or multilateral agreements; cost competitiveness; and technology transfer, logistical capability and ease-of-use. Given all of these factors, the time from conception to implementation of an alternative disinfestation treatment as a quarantine treatment for perishable and durable commodities can vary from 2 to more than 10 years, depending mainly on the technical difficulties. On the other hand, a pre-shipment treatment that, by definition, target non-quarantine pests may require less time for implementation if the proposed treatment is non-chemical, but it could be equally as long as a quarantine treatment if registration for use on foodstuffs is necessary.

Existing alternatives to MB for QPS treatment of perishable and durable commodities are based on (1) pre-harvest practices and inspection procedures; (2) non-chemical (physical) treatments; and (3) chemical treatments.

For perishable products, pest control based on pre-harvest practices must describe the cultural techniques leading to pest reduction, they must have an agreement on the area of the pest-free zones, and be subject to inspection in order to receive certification. In these cases, regulatory approval depends on a number of factors including knowledge of the pest-host biology, evidence of commodity resistance to the pest, trapping and field treatment results, monitoring of pests and diseases, and careful documentation. Some countries must also maintain a pest-free zone free of pests by placing restrictions on the movement of commodities into the zone and/or by disinfesting vehicles and commodities that are categorised as high risk before or on entry.

Non-chemical treatments kill pests by exposure to changes in temperature and/or atmospheric conditions, or high energy processes such as irradiation and microwaves, or physical removal using air or water jets. Often a combination of these is required to kill pests or pest complexes because they can tolerate a single treatment. Chemical fumigation QPS treatments are often technically feasible for both perishable and durable foodstuffs, but the range of chemicals is limited at present mainly because companies are reluctant to make submissions for registration due to the high costs of demonstrating compliance with health and safety standards and small market for the product. For non-foodstuffs (e.g. timber, cut flowers) that require a lesser investment in testing, alternative chemical treatments may be less expensive to develop.

For each category of alternative to MB, MBTOC noted country-specific regulatory agency approval for specific perishable and durable commodities or several commodities within a class (e.g. citrus): 24 *heat* treatments for 15 perishable commodities (babaco, cucumber, citrus, mango, papaya, bell pepper, eggplant, grapefruit, melon, narcissus, pineapple, squash, sweet potato, tomato and zucchini) and 33 heat treatments for 12 durable commodities (animal feed, bagasse, bulbs, grain, maize, horseradish, museum artefacts, packing material, rice straw and hulls, seeds, tobacco and timber); 7 *chemical* treatments for perishable commodities (asparagus, bulbs, cut-flowers, ornamental material) and 7 chemical treatments for durable commodities (bamboo, bulbs, cocoa, cotton, dried fruit, hay, ship holds and seafreight containers, seeds and dried pods, tick-infested articles, timber and logs, tobacco and wooden artefacts; more than 240 *cold* treatments for 27 perishable commodities (apples, apricots, avocado, carambola, cherries, citrus, clemantines, durian, ethrog, grapes, grapefruit, kiwifruit, litchi, loquats, nectarines, oranges, papaya, peaches, pears, persimmons, plums, plumcots, pomegranate, pommelo, quinces, tangerines and Ya pears) and 4 heat treatments for durable commodities (items infested with insects in soil, hickory, museum artefacts and pecans); one example of *controlled atmospheres* for perishable products (apples) and 12 treatments for 13 durable products (cocoa, dried figs, cereals, dried fruit, furniture, grain, museum artefacts, nuts, pulses, rice, seeds, spices and tobacco); 10 *combination treatments* for perishable products (apricots, cherimoya, durian, limes, litchi, ornamentals, seeds for planting and tomatoes) and one combination treatment for a durable commodity (timber, as logs); 5 examples of *irradiation* of perishable and durable commodities (garlic, papaya, carambola, litchi, plums, wooden artefacts); 30 examples of *pest-free zones* for 9 perishable commodities (cucurbits, grapes, kiwifruit, immature banana, melons, nectarines, peaches, strawberries and tomatoes); 6 examples of *pre-shipment inspection* for perishables (apples, apricots, cut-flowers, garlic, nectarines and vegetables); and three examples of the *systems approach* for perishables (apples, avocado and citrus). In summary, MBTOC noted more than 300 alternatives approved for quarantine treatment of perishables and more than 70 approved as QPS treatments for durable commodities.

Currently, there are no approved alternatives to MB for QPS for exports such as apples, pears, stonefruit and walnuts that are hosts to codling moth; for internal quarantine pests of berryfruit; for grapes infested with mites exported to some countries; for many root crops exported by countries if soil is present or pests of concern are detected on arrival; for cut-flowers (roses, carnations and statice) exported to Europe, USA, Scandinavia and Japan; for logs imported into the European Union potentially contaminated with oak wilt fungus; for ship hold disinfestation in most countries; and for seed-borne nematodes potentially infesting seeds for planting.

Reduction of Emissions from Methyl Bromide Use

Emissions from fumigation operations occur through leakage and permeation during treatment (inadvertent emissions) and from venting at the end of a treatment (intentional emissions). Estimates of the proportion of MB used that is released into the atmosphere vary widely because of: differences in usage pattern; the condition and nature of the fumigated materials; the degree of gas-tightness; and local environmental conditions. Some MB may also be converted to non-volatile materials making it incorrect to equate production with emissions.

Emission volume release and release rate to the atmosphere during soil fumigation depend on a large number of key factors. Of these, the type of surface covering and condition; period of time that a surface covering is present; soil conditions during fumigation; MB injection depth and rate; and whether the soil is strip or broadacre fumigated are considered to have the greatest effect on emissions. Under ideal conditions, when all these factors are controlled and impermeable films are used, emission volumes as low as 3% have been observed. It is unlikely, however, that these results will ever be repeated in the field due to the handling difficulties of laying plastic sheets during fumigation and leakage from the edges, tears, cracks and other events. The use of Virtually Impermeable Film (VIF) sheeting and reduced application rates of MB, offer the greatest potential for immediate reduction of emissions from soil fumigations during the interim phaseout period and for any post-phaseout critical use exempted treatments. Use of VIF has been mandated in the EU. However, elsewhere, cost and several non-air quality related environmental and health issues (recycling, disposal and possibility of increased bromide ion concentration in soil) are seen as barriers to their adoption.

For commodity and structural fumigations, techniques such as improved sealing of enclosures for decreasing MB leakage are in limited use world-wide. Their adoption is constrained particularly by lack of incentives, lack of promotion of relevant technologies and by perceived or real increases in costs and logistical problems. A high degree of containment is a prerequisite for efficient recovery of the used MB. Many facilities used for fumigating perishables, particularly for quarantine, already have a high standard of gastightness leading to very low leakage rates (often less than 5% of applied dosage).

There has been limited research into the development of recovery and recycling systems for MB. Systems reported on in the 1998 MBTOC report would have had high running costs associated with energy requirements and many would require a level of technical competence to operate, not normally found at fumigation facilities. Since then two systems based on activated carbon absorption have been commercialised. There are now several examples of recovery equipment in current commercial use. Adoption of these systems has been driven by considerations other than ozone layer protection, e.g. local air quality.

Practically, the scope for recovery of MB after fumigations is likely to be restricted to treatments carried out in enclosures, i.e. space fumigations of commodities, structures and transport, with subsequent destruction of the captured MB. At this time no system for recovery of MB from soil fumigation has been commercialised and there are no systems known to MBTOC under development. Furthermore, since the phaseout of MB for soil uses in non-Article 5(1) countries is imminent (2005), such systems are unlikely to be developed. In 2000, total space (durables, perishables and structures) treatments in Article 5(1) and QPS uses in non-Article 5(1) countries were 10,600 - 12,300 tonnes. On the basis of 70% recapturable MB, this corresponds to about 8,000 metric tonnes of emissions that could be prevented from entering the atmosphere by the fitting of recapture and destruction equipment.

Unlike some other ozone depleting substances where the interim needs of Article 5(1) countries can be met in part by banks of recycled material, it is unlikely that this method will be practical for MB. This is because some of the MB used in any application reacts and breaks down (it is not unusual to lose most of the MB applied in some more reactive commodities such as oilseed meals). Some Parties may not permit reuse of recaptured MB as it does not conform to their labelling requirements.

If recovery is to be recognised as an acceptable method of reducing MB emissions to the atmosphere, it will be necessary to set specifications on aspects of fumigation such as equipment efficiency and acceptable levels of emission.

Chapter

2

Introduction to the Assessment

2.1 Methyl Bromide

Methyl bromide (MB) is a fumigant that has been used commercially for more than 50 years to control a wide spectrum of pests including fungi, bacteria, soil-borne viruses, insects, mites, nematodes and rodents. A major amount of MB is used for soil fumigation, a moderate amount for disinfestation of durable and perishable commodities, while a minor amount is used for disinfestation of buildings, ships and aircraft.

MB has features that make it a versatile and convenient material for many pest control applications. In particular, it is quite penetrative, reaching pests located in relatively inaccessible locations in soil, commodities, buildings and vehicles. Treatment periods including venting and aeration vary from 2-3 hours to several days according to target pest(s), the concentration required for efficacy and other specifications and regulations.

Although MB is clearly a most useful pest management technique in specific instances, it was listed under the Montreal Protocol as an ozone depleting substance (ODS) in 1992. A phaseout schedule was subsequently agreed by Parties (Table 2.1).

There are also a number of concerns, apart from ozone depletion, that have led countries to impose restrictions on its use. These concerns include: residues in food; toxicity to humans and associated operator safety and public health; and detrimental effects on soil biodiversity. In some countries, pollution of surface and ground water by MB and derived bromide ion is also of concern.

2.2 MBTOC Mandate

The Methyl Bromide Technical Options Committee (MBTOC) was established in 1992 by the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer to identify existing and potential alternatives to MB. MBTOC, in particular, addresses the technical feasibility of chemical and non-chemical alternatives for the uses of MB, apart from its minor use as a chemical feedstock. MBTOC reports to the Technology and Economic Assessment Panel (TEAP) that advises the Parties on scientific, technical and economic matters related to ozone depleting substances and their alternatives.

Information contained in MBTOC's reports contributes to the Parties' deliberations on appropriate controls for MB.

Table 2.1 Phaseout schedule agreed at the Ninth Meeting of the Parties in 1997

Year	Non-Article 5(1)	Article 5(1)
1991	Consumption baseline	
1995	Freeze	
1995-98 average		Consumption baseline
1999	25% reduction	
2001	50% reduction	
2002		Freeze
2003	70% reduction	Review of reductions
2005	Phaseout	20% reduction
2015		Phaseout

Critical and emergency uses may be permitted after phaseout if they meet agreed criteria.
Quarantine and pre-shipment (QPS) uses are exempt from reductions and phaseout.

Decisions encouraging advanced phaseout:

- Countries may take more stringent measures than those required by the schedules (Article 2 of the Montreal Protocol).
- In applying the QPS exemption, all countries are urged to refrain from use of MB and to use non-ozone-depleting techniques wherever possible (Decision VII/5).
- A number of developing and industrialised countries signed Declarations in 1992, 1993, 1995 and 1997 stating their determination to phase out MB as soon as possible.

2.3 Committee Process and Composition

At December 2002 MBTOC had 34 members; 10 (29%) from developing and 24 from developed countries and coming from 9 Article 5(1) and 10 non-Article 5(1) countries respectively. Representation from diverse geographic regions of the world promotes reasonably balanced documentation of alternatives to MB, based on the wide-ranging expertise of Committee members. Most Article 5(1) MBTOC and many non-Article 5(1) members were nominated by their governments.

MBTOC members participate in a personal capacity as experts and do not function as representatives of governments, industries, non-government organisations (NGOs) or others. Members of MBTOC contribute substantial amounts of work in their own time. For construction of this Assessment report, MBTOC met formally in Brussels (2001) and Acapulco (2002). To produce each chapter as efficiently as possible, MBTOC members were divided into sub-committees and topics affecting all chapters were discussed and agreed in plenary. Much of the text of this Assessment was drafted in committee during the formal meetings. Additionally the work was progressed through informal meetings associated with international conferences (San Diego 2001, Orlando 2002). The Assessment was finalised by email, to produce a consensus document of the Committee.

MBTOC members and sub-committee chairs for the working groups within MBTOC are listed in Appendix 1. The subcommittee chairs acted as coordinators and lead authors for the main chapters of this Assessment.

2.4 UNEP Assessments

The first interim assessment for the Protocol on MB was completed in 1992. A full assessment of the alternatives to MB was completed in 1994 and reported to the Parties in 1995 (MBTOC 1995) as a result of Decisions taken at the fourth Meeting of the Parties to the Montreal Protocol held in Copenhagen. The second MBTOC Assessment was presented to Parties in 1998 (MBTOC 1998). MBTOC progress reports on advances in alternatives to methyl bromide and other issues related to methyl bromide were included in annual TEAP reports to the Parties (1999, 2000, 2001, 2002). An index to methyl bromide alternatives discussed in TEAP and MBTOC reports can be found at http://www.teap.org.

Under Decision XI/17, taken at the ninth Meeting of the Parties to the Protocol in 1997, the Parties requested the Assessment Panels, to update their 1998 Assessment reports and submit them to the Secretariat for consideration by the Open-Ended Working Group and by the fifteenth Meeting of the Parties in 2003.

This MBTOC 2002 Assessment reports on MB usage; the quantities produced and consumed; existing and potential alternative treatments for uses as a soil fumigant; as a fumigant of durable commodities and structures; and as a fumigant for quarantine and pre-shipment (QPS). It includes methyl bromide-related material from the annual updates provided by TEAP.

In addition, the report provides sections in response to Decision IX/5(1e) and also on methods for reducing MB emissions. Decision IX/5(1e) notes that, in the light of an assessment to be made by the Technology and Economic Assessment Panel, the Meeting of the Parties shall decide in 2003 on further specific interim MB reductions in Article 5(1) Parties for the period beyond 2005. To aid this assessment, information is provided on the extent to which alternatives have been tested and evaluated in Article 5(1) countries, and the results of demonstration projects which examined efficacy with respect to target pests, ease of application, availability, relevance to climatic conditions, soils and cropping patterns found in Article 5(1) regions.

2.5 Definition of an Alternative

In this report, MBTOC defined alternatives as:

> *' those non-chemical or chemical treatments and/or procedures that are technically feasible for controlling pests, thus avoiding or replacing the use of MB. 'Existing alternatives' are those in present or past use in some regions. 'Potential alternatives' are those in the process of investigation or development.*
>
> *MBTOC assumed that an alternative demonstrated in one region of the world would be technically applicable in another unless there were obvious constraints to the contrary e.g., a very different climate or pest complex.*
>
> *MBTOC is not required in its terms of reference to conduct economic studies on MB and alternatives. Additionally, it was recognised that regulatory requirements, environmental issues and social constraints may make an alternative unavailable in a specific country or region. MBTOC did not omit alternatives from consideration on such grounds.'*

2.6 Report Structure

Chapter 3: Methyl Bromide Production, Consumption and Limitations on Use provides information on the technical and legislative restrictions on MB use and consumer/market limitations in addition to information on production and consumption by sector.

Chapter 4: Alternatives to Methyl Bromide for Soil Treatment covers a range of alternatives for this currently major MB-use area. Discussion includes:

- Cultural practices (crop rotation, soilless culture, organic amendments, biofumigation, planting time, water management and flooding, mulching, cover crops and sanitation).

- Biological control, plant growth promoting rhizobacteria, resistant plant varieties and grafting of annual and perennial crops.

- Physical methods such as soil solarisation and steam treatments.

- Strategic applications of specific pesticides.

- Combination treatments for obtaining greater efficacy and reducing dosage.

Chapter 5: Alternatives to Methyl Bromide for Treatment of Durables, Wood Products and Structures includes discussion on:

- Alternative fumigants (in-kind replacements for MB)

- IPM approach combining several different measures.

- Controlled atmospheres and vacuum technologies.

- Physical measures such as mechanical treatments, cold, heat, irradiation and inert dusts.

- Contact insecticides for persistent protection against re-infestation.

- Biological agents and botanical compounds as part of IPM systems.

Chapter 6: Alternatives Evaluated in Article 5(1) Countries – Report on Decision IX/5(1e) provides information in response to Decision IX/5(1e) and highlights key factors facing developing countries including:

- MB usage trends.

- MB projects supported by the Multilateral Fund and others.

- Results of demonstration projects on MB alternatives.

- MB phaseout projects and scheduled MB reductions.

- Examples of alternatives in commercial use.

Chapter 7: Quarantine and Pre-shipment covers MB and alternative treatments for Quarantine and Pre-shipment (QPS) of durable and perishable commodities, including discussion of :

- existing MB treatments.

- approved alternative treatments.
- situations where MBTOC did not identify alternatives.

Chapter 8: Reducing Methyl Bromide Emissions discusses:

- Inadvertent and intentional MB emissions.
- Emissions estimated from soil, perishable and durable commodities and structural treatments.
- Containment techniques.
- Developments in MB recovery and recycling systems.

Chapter 9: Case studies on MB alternatives in commercial use contains descriptions of applications of MB alternative technology in various circumstances, covering:

- Fruit and vegetable production.
- Ornamentals and tobacco
- Postharvest applications.

The *Appendix* contains:

- List of MBTOC members and their contact details (Appendix 1).

2.7 References

MBTOC. 1995. 1994 Report of the Methyl Bromide Technical Options Committee: 1995 Assessment. UNEP: Nairobi. 304pp.

MBTOC. 1998. Report of the Methyl Bromide Technical Options Committee. 1998 Assessment of Alternatives to Methyl Bromide. UNEP: Nairobi. 374pp.

TEAP. 1999. April 1999 Report of the Technology and Economic Assessment Panel. UNEP: Nairobi. 245pp.

TEAP. 2000. Report of the Technology and Economic Assessment Panel. April 2000. UNEP: Nairobi. 193pp.

TEAP. 2001. Report of the Technology and Economic Assessment Panel. April 2001. UNEP: Nairobi. pp. 1 - 112.

TEAP. 2002. Report of the Technology and Economic Assessment Panel. April 2002. Vol. 1. Progress Report. UNEP: Nairobi. 181pp.

Chapter

3

Methyl bromide production, consumption and limitations on use

3.1 Introduction

Methyl bromide (MB) has features that make it a versatile and convenient material for many pest control applications. Exposure periods and concentrations depend on the system under treatment and the target pest(s); and quarantine, contractual, regulatory and other specifications.

This chapter has been written in 4 sections. The first gives a general overview of the uses of MB; the second discusses production and supply; the third consumption and usage by sector and application methods; and the final section discusses the technical and legislative limitations affecting further use of MB including market forces, food retailer policies, eco-labelling and levies.

3.2 Uses of Methyl Bromide

For uses that exceed 400 tonnes per annum worldwide, MB can be divided into the following categories:

In soil:

- as a preplant treatment against insect, nematode and fungal pests and for weed control in production of cut flowers, strawberries, cucurbits, tomatoes, peppers and eggplant;
- as a replant treatment for vines or deciduous fruit trees against 'replant disease';
- as a treatment of seed beds principally against fungi for production of a wide range of seedlings, notably tobacco;
- as a treatment to ensure production of pest-free propagation stock, e.g. strawberry runners.

In durables:

- as a treatment against insect pests for cereal grains and similar commodities in storage to restrict damage to the commodity and at point of import or export as quarantine, phytosanitary or contractual measures;

- to control pests of dried fruit and nuts in storage and trade;
- as a quarantine measure for treatment of exported or imported timber and wooden pallets, principally against insects and some fungal pests.

In perishables:

- as a phytosanitary or quarantine treatment against insect pests in many fresh fruit, vegetables and cut flowers in export trade.

In structures and transport:

- as a treatment for food facilities, flour mills and other buildings against established insect infestations;
- as a treatment of ships and freight containers, either empty or containing durable cargo, against rodents and insect pests, often as a quarantine or contractual measure.

3.3 Production and Supply

MB has a boiling point of 4°C under normal atmospheric pressure. It is normally supplied and transported as a liquid in pressurised steel cylinders or cans. Typically the cylinders range in size from 10 kg to 200 kg capacity. There is also trade in larger cylinders of up to 18 tonne capacity and in small disposable steel cans, typically of 0.4 – 1 kg capacity. Decision VIII/14 recognises supply in all of these forms as 'trade in bulk'. MB is usually applied directly from the cans or cylinders in which it is transported, though it may also be decanted from large cylinders and directly applied. Decanting is not permitted in some countries. Supply in small disposable cans or cylinders is common in some regions of the world.

3.3.1 Production for all uses

Estimates of MB production for all purposes, from 1984 to 2000, are given in Table 3.1 and graphed in Figure 3.1. The figures for 1984-1996 were previously reported by MBTOC (1995), while figures from 1997-2000 were derived from the Ozone Secretariat data available in 2002. Gaps in the data set, where possible, were filled by carrying forward estimates from previous years. The estimates presented in Table 3.1 are the best available to MBTOC at this time. However, several gaps and inconsistencies remain, and industry sources indicate that the total production might possibly be significantly greater than the figures reported below.

The global production of MB for all uses in 1998 (including QPS and feedstock), as reported to the Ozone Secretariat in 2002, was about 75,200 tonnes. Taking account of the gaps in the data set, production was likely to have been at least 75,727 tonnes in 1998. Global production in 2000 was estimated to be approximately 70,000 tonnes. While MB production for fumigant uses, including for QPS uses, appears to have been reduced in 2000, production for chemical feedstock appears to have tripled compared to previous years.

Table 3.1 Reported production (metric tonnes) of methyl bromide, 1984-2000

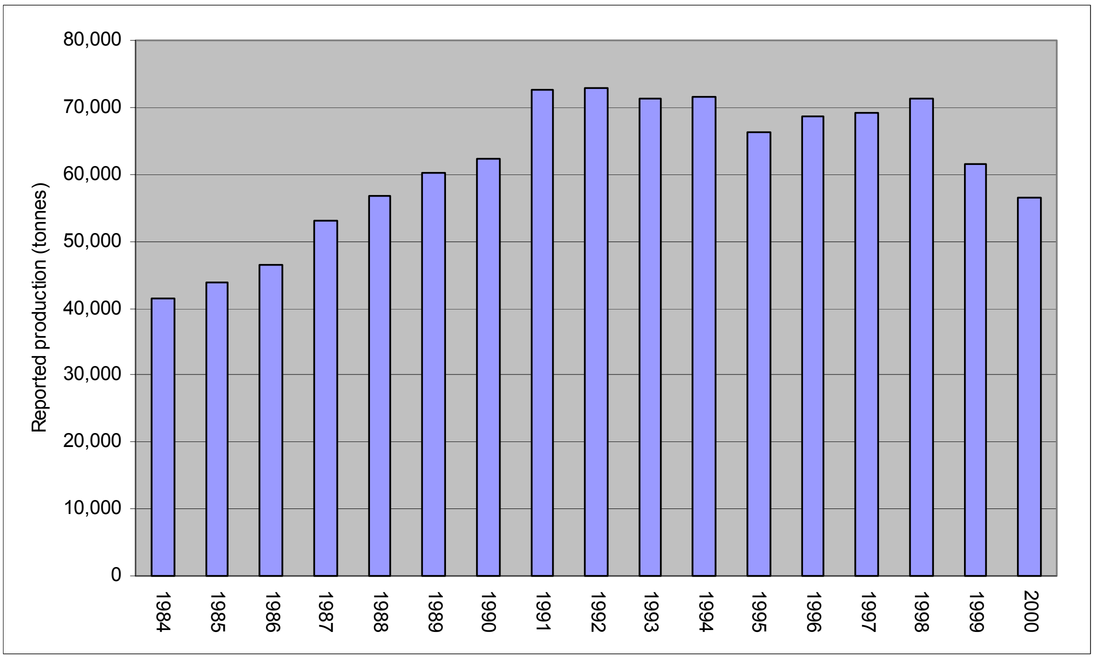
Year	Chemical feedstock	Fumigant, including for QPS	Total production
1984	3,997	41,575	45,572
1985	4,507	43,766	48,273
1986	4,004	46,451	50,455
1987	2,710	52,980	55,690
1988	3,804	56,806	60,610
1989	2,496	60,074	62,570
1990	3,693	62,206	65,899
1991	4,071	72,689	76,760
1992	2,658	72,967	75,625
1993	3,000	71,157	74,157
1994	3,000	71,621	74,621
1995	2,458	66,339	68,857
1996	2,759	68,666	71,425
1997	3,000(a)	69,209	72,209 (b)
1998	4,448	71,279	75,727 (b)
1999	4,453	61,391	65,844 (b)
2000	13,132	56,599	69,731 (b)

(a) estimate

(b) Industry sources indicate that total production might be significantly greater than the figures reported in this table.

Data Sources: 1984–1996: Estimates from MBTOC 1998 Assessment. 1997–2000: Estimated from Ozone Secretariat data of April & October 2002; gaps in data set were filled by carrying forward estimates from previous years where possible

Figure 3.1 Trend in global reported production of methyl bromide for fumigant uses (tonnes)



3.3.2 Production for controlled uses

Global: Ozone Secretariat reports to date indicate that global production for controlled uses of MB (i.e. excluding feedstock and QPS) was at least 62,750 tonnes in 1998. Other sources indicate that it was higher. Global production for controlled uses was estimated to be at least 49,560 tonnes in 1999 and about 46,120 tonnes in 2000, as preliminary estimates.

Non-Article 5(1) regions: In line with Montreal Protocol requirements, non-Article 5(1) countries have reduced their controlled production from about 66,000 tonnes in 1991 (baseline) to about 32,050 tonnes in 2001, representing a reduction of 51%.

Article 5(1) regions: Article 5(1) production increased from approximately 445 tonnes in 1991 to an estimated average of 1,324-1,400 tonnes in 1995-98 (baseline). Production in China increased substantially in the 1990s following a joint partnership agreement with an Israeli MB producer. Article 5(1) production was about 2,572 tonnes in 2000, accounting for about 6% of production for controlled uses. Initial reports for 2001 show that MB production in Article 5(1) countries was around 2,500 tonnes, indicating that the upward trend may have halted in the production for controlled uses.

3.3.3 Regions of production

MB is currently produced in 3 Article 5(1) countries (China, India and Romania) and 5 non-Article 5(1) countries (France, Israel, Japan, Ukraine and USA), as indicated in Table 3.2. The list of MB manufacturers may not be complete. In the past, production also occurred in the Democratic People's Republic of Korea, but MB production ceased around 1995 (Pak Chun Il, pers. com, 1999).

Israel and the USA remain the major producers, accounting for 44% and 37%, respectively, of global production for controlled uses. Together, the USA and Israel accounted for 81% of controlled production in 2000.

Table 3.2 Methyl bromide manufacturing companies and countries

Country	MB manufacturers in 2000
China	Lianyungang Seawater Chemical First Plant / Lianyungang Dead Sea Bromine Co. Ltd, Jiangsu Province Linhai Jianxin Chemical Co Ltd, Zhejiang Changui Chemical Plant, Shandung
France	Elf Atochem SA, France
India	M/S Tata Chemicals Ltd, Mithapore, Gujurat State
Israel	Dead Sea Bromine Ltd, Beer Sheva
Japan	Teijin Chemicals Ltd, Mihara, Hiroshima Prefecture Sanko Chemical Industry Co. Ltd, Samukawa, Kanagawa Prefecture Nippoh Chemicals Co Ltd, Isumi, Chiba Prefecture Dohkai Chemical Industry Co. Ltd, Kitakyushu, Fukuoka Prefecture Chemicrea Co Ltd, Chiba, Chiba Prefecture
Romania	SC Sinteza SA, Oradea
Ukraine	Saki Chemical Plant, Saki, Crimea
USA	Great Lakes Chemical Corp, Arkansas

3.4 Consumption and Usage

3.4.1 Reported consumption for controlled uses

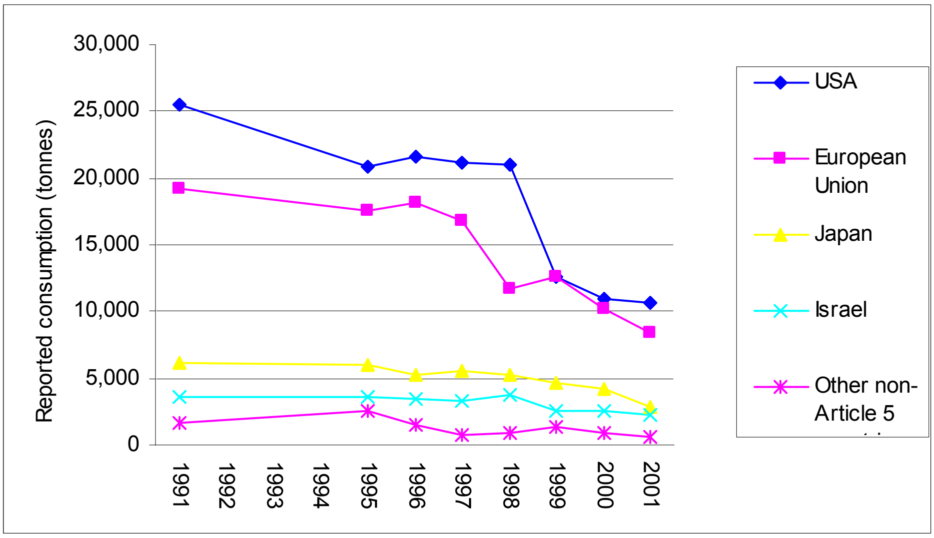
Global: Global consumption of MB for controlled uses was estimated to be about 64,550 tonnes in 1991 and remained above 60-63,000 tonnes until 1998. On the basis of Ozone Secretariat data available in October 2002, global consumption was estimated to be at least 60,200 tonnes in 1998, 49,170 tonnes in 1999 and 45,360 tonnes in 2000.

Non-Article 5(1) regions: Controlled MB consumption in non-Article 5(1) countries has been reduced from about 56,100 tonnes in 1991 (baseline) to about 28,900 tonnes in 2000. The data set for consumption in 2001 is virtually complete and indicates that consumption was less than 24,820 tonnes, representing a 56% reduction from the baseline. This indicates that non-Article 5(1) regions have reduced MB consumption in advance of the Montreal Protocol schedule, i.e. 50% reduction in 2001. Figure 3.2 shows the trend in MB consumption in non-Article 5 regions.

Article 5(1) regions: Figure 3.3 shows the trends in Article 5 regions. Controlled MB consumption in Article 5(1) countries rose from about 8,460 tonnes in 1991 to about 17,600 tonnes in 1998, representing an increase of about 15% per year on average. However, based on data available to date, Article 5(1) consumption was reduced to about 16,440 tonnes in 2000, indicating an annual average reduction of about 3% per year between 1998 and 2000. While certain Article 5(1) countries continue to increase consumption, national consumption was reduced by more than 20% in some Article 5(1) countries in the period 1998-2000.

Consumption in Article 5(1) regions is expected to rise overall during 2001 and then fall rapidly from 2002 as a result of MB phaseout projects currently being implemented. By December 2002 the Multilateral Fund had approved 38 MB phaseout projects which are designed to eliminate almost 8,000 tonnes of MB in Article 5(1) countries. The projects are scheduled to phaseout about 75% of this tonnage before 2006. Additional projects are under development. The existing and anticipated projects are due to lead to the phaseout of about 10,000 tonnes MB before about 2007, eliminating more than 50% of the peak consumption in Article 5(1) regions.

Figure 3.2 Trend in reported MB consumption in non-Article 5(1) countries (tonnes)



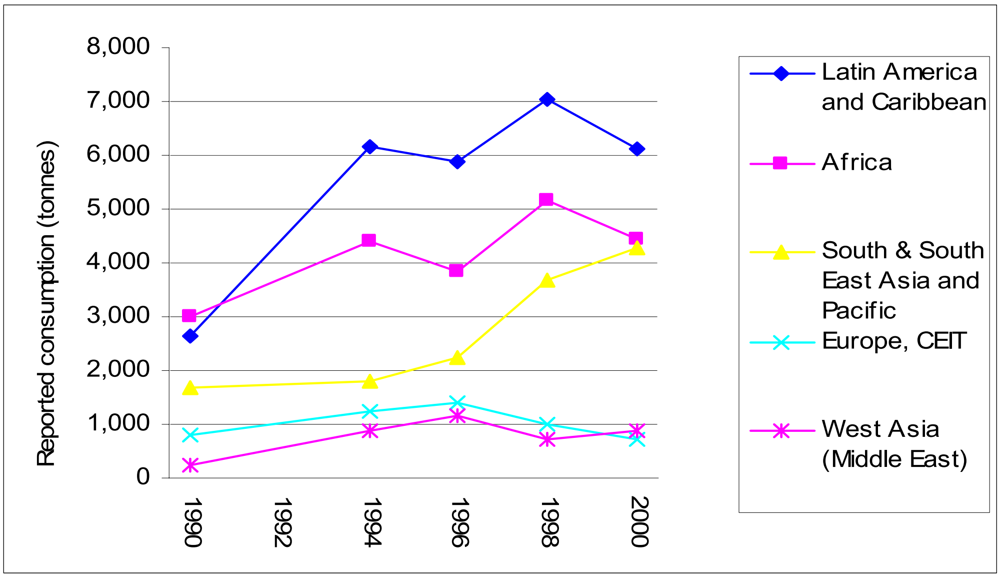
Footnote: MB use in Israel in 1995-6 was assumed to be same as in 1991, although official statistics report negative MB consumption.

3.4.2 Usage by sector

A MBTOC survey of ozone offices and national experts in 2001/02 provided information on the breakdown of MB uses in major MB-consuming countries in 2000, a sample covering about 70% of global MB use. The results of this sample indicated that approximately 74% was used for soil and approximately 26% for commodities/structures, including QPS. The estimated proportions for major sectors were: soil 74%, durable commodities 15%, perishable commodities 8.5% and structures 2.5% (shown in Figure 3.4). The relative proportions appear to have changed little since the MBTOC Assessment in 1994, which provided estimates as follows: soil 75%, durable commodities 13%, perishable commodities 9% and structures 3%.

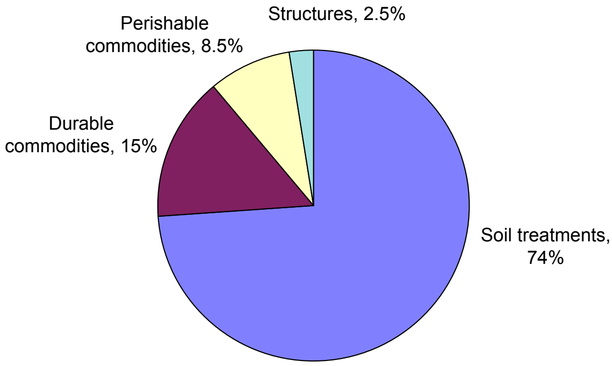
With almost all use of MB on perishables and an estimated 80% of that on durables falling into the uncontrolled QPS category, it can be seen that soil treatments comprise about 93% of controlled uses.

Figure 3.3 Trend in reported MB consumption in Article 5(1) regions (tonnes)



Footnote: Regions in this figure correspond to the regions of UNEP's ozone networks.

Figure 3.4 Analysis of global methyl bromide fumigant use by major sector, 2000 estimate, including QPS.



3.4.3 Quarantine and pre-shipment

The Ozone Secretariat data shows that more than 11,410 tonnes MB was produced for QPS in 1999, and other estimates indicate that production for QPS may have been about 11,825 tonnes. Information available to date for 2000 indicates a range of 10,475 – 11,800 tonnes MB production for QPS purposes, accounting for about 19-21% of fumigant production. When the figures are estimated on the basis of use data (see Table 7.1), rather than production reports, the estimated range for QPS consumption is 10,600 - 12,300 tonnes, accounting for about 19 - 22% of global consumption in 2000. Thus the production-based and consumption-based estimates are in good agreement, given the uncertainties involved in both estimates. In Article 5(1) regions the percentage of MB used for QPS is higher than in non-Article 5(1) regions.

In some countries the proportion of MB used for QPS is greater than 25% of national consumption. The use of MB for QPS continues to increase in specific countries and sectors, notably for the treatment of timber pallets.

However, in recent years QPS uses have also been reduced substantially in certain countries, as the following examples illustrate:

- Japan reduced its use of MB for QPS from 2703 tonnes in 1994 to 1480 tonnes in 2001 (-45% change)
- Israel reported QPS of 853 tonnes in 1997 and 319 tonnes in 2000 (-62% change)
- Mexico reported QPS of 1252 tonnes in 1997 and 359 tonnes in 2000 (-71% change)

3.5 Application Methods

3.5.1 Soil fumigation

MB is applied by manual application or mechanised injection.

Manual application: Manual application involves applying MB to soil which has been pre-tarped with plastic sheets. The main method in this application is the so-called ‘hot gas’ method where liquid MB from cylinders under pressure is vapourised in a heat exchanger and then introduced under the plastic covers.

World wide, except for the USA and several other countries, this is the principal method of application and almost exclusively the method used in fumigating soil in greenhouses (glass and plastic houses). In many countries, this method is widely used for outdoor fumigation. In some situations, field fumigation is carried out with mulched strips (strip fumigation) of 0.8 - 1.2 m wide, particularly for row crops such as cucurbits, tomatoes and peppers.

When applied from small steel cans of less than 1 kg capacity, MB is not normally vapourised, but discharged directly from the can under its own pressure, preferably using a specially developed opener. This can be done so as to release MB under the plastic cover without damage to the cover.

MB is often supplied as a mixture containing 2% chloropicrin, added as a warning agent in many instances to comply with national safety regulations.

Mechanised injection: The second method involves mechanised injection and is the principal method used in the USA, several European countries, Israel, Australia and South Africa. MB from cylinders is applied by injecting the fumigant at a controlled depth, typically 10 - 25 cm into the soil (called ‘shallow injection’) the treated area being simultaneously sealed by plastic sheeting. The process is normally carried out as a broad-acre fumigation where one sheet is glued to the previous one. However, some MB application is done under strips of plastic with the edges of the strips buried by the machinery in the soil.

Another system of mechanised injection is 'deep injection' (approximately 80 cm depth) of MB without covering the area with plastic sheets. Deep injection of MB is carried out mainly prior to planting and replanting in deciduous orchards, vineyards and other plantations, mainly in the USA.

A variety of mixtures of MB and chloropicrin are used in this type of fumigation. Until recently the predominant mixture used was MB containing 2% chloropicrin. The chloropicrin was added as a warning agent, not as an active ingredient. With restriction of supplies of MB under the Montreal Protocol control measures there is now a much increased use of formulations of MB with high concentrations of chloropicrin, typically 30 - 70% chloropicrin, with the chloropicrin added as an active agent (see Chapter 4). High concentrations of chloropicrin are in use particularly in non-Article 5(1) countries.

3.5.2 Commodities and structures

MB is applied to commodities (durables and perishables) and structures either as a vapourised gas or directly from the cylinder supply. In the latter process, MB is typically applied directly from the cylinder through a narrow bore application line (or series of lines) culminating in an atomising jet or series of jets which are designed to enhance the speed of vaporisation of the fumigant. The rate at which the liquid fumigant becomes a vapour is largely dependent on the ambient air temperature. These lines and jets are laid out either on the commodity, or throughout the structure, to try to ensure an even distribution of fumigant. Alternatively, MB is passed through a heat exchanger which vaporises the fumigant before it is applied through suitably perforated distribution pipes, again laid out in such a way to facilitate even MB distribution.

The dose of MB is calculated according to label, contractual, or legislative (e.g. quarantine) requirements. The required dose is applied by weighing the cylinder of liquid MB and allowing the correct amount to be released, taking into account the volume of space and commodity.

In the case of fumigation facilities for commodities, this will vary from well-sealed, purpose-built fumigation chambers (portable and fixed) to very poorly sealed bagged stacks. In between these extremes, are ships' holds (sometimes very well sealed, but not always); freight containers (often not very gastight); and well-sealed bagged stacks with laminated sheeting (can be very gastight).

In the case of structural fumigation, the gastightness varies from aircraft (often very gastight); ships' holds; modern food factories and mills (can be very gastight); to older buildings such as many flour mills (often not very gastight and in many cases, impossible to make more than partially gastight).

Normally, in all these situations fumigation is carried out for a predetermined period to try to ensure sufficient time for MB to penetrate to the target pest(s) and that the *ct*-product needed to eradicate all stages of the pest life cycle has been achieved in the most difficult-to-penetrate part of the enclosure under treatment.

Technology exists to enable the *ct*-product to be monitored during the fumigation. Generally, much lower doses can be utilised in many cases to achieve the same results compared with unmonitored treatments as the allowance for errors and poor distribution can be lessened. The concentration must be achieved in critical areas of the treatment enclosure, e.g. in the centre of the commodity bulk. Quality assurance programmes will normally specify that concentrations are monitored, but in practice monitoring is rarely carried out as it is normally cheaper to use more MB than to measure concentration and adjust treatment accordingly.

In structures, such as buildings, ships and aircraft, the same principles and application techniques apply, but the target *ct*-product must be set to include the floors, walls and machinery where deep-seated and poorly accessible pests are to be controlled. Accurate monitoring, lower doses and the ability to add more fumigant are increasingly becoming more widely used, rather than the still widely practiced method of over-dosing to try to guarantee success.

In many countries, commodity and structural treatments are now carried out with 100% MB formulations, superseding formulations containing 2% chloropicrin.

3.6 Limitations on Methyl Bromide Use

3.6.1 Technical limitations

Although MB is well recognised as being a most useful fumigant, there are a number of technical factors that restrict its application. Not only have these tended to limit its field of application, apart from direct economic considerations, but some have also led to legislative and other restrictions independent of its detrimental effect on the ozone layer.

MB can have adverse effects on a number of commodities, causing taint and odours. These are listed in Bond (1984). It also has substantial phytotoxicity. This makes it an effective treatment for controlling weeds, but can limit its usefulness in control of pests of growing plants and perishable commodities, sometimes resulting in reduced storage life (e.g. of cut flowers) or preference for alternatives.

Treatments with MB result in production of bromide ion residues. These may accumulate to excessive levels in commodities that are fumigated several times. In the case of soil fumigation, bromide ion residues have been a cause for concern in surface or ground water in some European countries, such as the Netherlands.

A major limitation to MB use is its toxicity to humans. Many countries restrict the actual application of MB to trained and licensed fumigators. The regulations may specify appropriate safety equipment and airing times for removal of residual gas after treatments. Additionally, there may be stringent controls on allowable concentrations in workspaces and in the environment around fumigation sites. The toxicity to humans has been reviewed in detail (WHO/IPCS 1995).

3.6.2 Legislative limitations

A number of countries have introduced regulations or policies that restrict the use of MB more than the Protocol requires at this stage. Some have introduced restrictions in response to its status as an ozone-depleting substance (ODS) but others such as the Netherlands put restrictions in place in response to concerns over local environmental contamination (mainly MB in the local air and bromide ion residues in the surface water).

The Government of Japan implemented the following controls on MB production in advance of the Protocol schedule: 5% reduction in 1996, 10% reduction in 1997, 15% reduction in 1998, and 30% reduction in 2000 (Tateya 2003). In order to prevent the MB intended for QPS being diverted to other uses, Japan requires special red labels to be placed on MB containers intended for QPS, while the MB containers intended for soil and other non-QPS fumigant purposes carry a blue label. An exclusive system has been established for delivery of MB from the local producers to quarantine fumigation operators, together with other measures to prevent QPS MB being used for non-QPS purposes (Tateya 2002).

The European Union implemented a 25% cut in the production and supply of MB in 1998, a year earlier than the Protocol schedule. The EU Regulation (EC 2073/2000) on substances that deplete the ozone layer introduced several other controls on MB that are more stringent than international requirements. In particular, there is an accelerated phaseout consisting of a 60% cut in production and consumption from January 2001, and a 75% cut from January 2003. From January 2001, the Regulation limited the quantity of MB that can be used for QPS. EU Member States are obliged to report annually to the European Commission on progress being made in evaluating and adopting alternatives for QPS (Batchelor 2002).

In 1994, Denmark approved a Regulation to phaseout its major use of MB (greenhouse tomatoes) by 1996 and to phaseout all remaining uses by 1998 (Ministry of the Environment 1994). The Regulation does not provide an exemption for QPS use. The Ministry may grant permission for MB fumigation to be carried out in exceptional circumstances, if an applicant can prove no alternatives can be used and that efforts have been made to develop an alternative. Denmark successfully completed its phaseout of MB by January 1998 (Ministry of the Environment 1998).

The Dutch horticulture industry relied heavily on MB in the past, using about 3,000 tonnes of MB for intensive production of crops such as strawberry, tomato and cut flowers. However, the Netherlands completed its phaseout of MB as a soil fumigant by 1992, with restricted uses still permitted for some commodity and specialist treatments. Official statistics show that the yield and value of horticultural production was maintained and increased over the period of phaseout (Prospect 1997). It was found that the removal of MB benefitted the horticultural sector in the Netherlands because it acted as a catalyst for the widespread and on-going development of innovative, modern production techniques (De Barro 1995, Van Haasteren 1998).

A regional government in Italy prohibited the use of MB in an intensive horticultural area near Lake Bracciano in the 1980s, due to concerns about contamination of the lake (Rome Province 1983). University researchers and regional bodies for agricultural development assisted with the introduction of alternatives. In 1994 Italy's Health Ministry issued a national Ordinance that prevented annual soil fumigation by permitting fields to be fumigated only once in any 24 month period (Ministro della Sanita 1994).

Several Article 5(1) countries have introduced regulations to restrict the use of MB. Countries that are implementing MB phaseout projects under the Multilateral Fund have made firm commitments to achieve early phaseout of major MB uses, and in some cases, all MB uses, as a condition of receiving funds (see Chapter 6).

A number of Article 5(1) countries have previously restricted use of MB because of safety concerns. Belize, for example, used limited amounts of MB in the past for grain fumigation, but use of MB was prohibited by pesticide controls except for QPS because it was considered 'highly toxic to man' among other factors (Pesticides Control Board 1998). Tunisia has not registered MB as a soil fumigant, so it cannot be used for soil (M. Besri *pers. comm*.).

3.6.3 Consumer/market preferences

In addition to technical and legislative limitations, there are a number of commercial and market limitations on the use of MB. Decision VII/29 of the Parties requested that TEAP provide information on possible uses of market-based measures relating to MB (TEAP 1997). This section up-dates information on market measures, covering government promotion of market mechanisms and cases where companies have provided leadership in reducing reliance on MB.

3.6.3.1 Importance of market factors in phaseout

A Multilateral Fund study has identified the importance of market factors in the timing and success of phaseout for ozone-depleting substances (ODS): ‘The first primary factor affecting the phaseout relates to the markets for ODS technologies and the associated alternatives. Various market forces drive enterprises to stop using ODS. These include, for example, international and domestic trade pressures and the prices of both ODS and alternative technologies. The nature and direction of these forces play an important role...’ (UNEP 1994).

TEAP identified the significant role of market factors and voluntary actions by leadership companies, when it reviewed the lessons from phaseout of CFCs and halons in industrialised countries. TEAP noted that many experts and users in 1987 felt CFCs and halons would be largely irreplaceable. In retrospect, these early perspectives failed to appreciate the potential for technical innovation, the power of market forces, the efficiency of public/private partnerships, the influence of chemical companies and user industries that supported ozone-layer protection, and the leadership of specific companies that pledged early phaseout (TEAP 1995).

Users, suppliers, supermarkets and manufacturers in some regions have adopted, or are starting to adopt, alternatives in response to concerns about ozone depletion or as part of policies to reduce reliance on pesticides in general. Market changes, such as the ones identified below, are likely to become more prevalent as companies and the public become more aware that MB is a controlled ODS.

3.6.3.2 Users and pest control companies taking leadership in alternatives

In recent years, farmers and pest control suppliers in some regions have adopted alternatives reported in other chapters of this Assessment. In some cases, users have taken a significant leadership role in adopting alternatives and examples include the following:

- A major US pest control company, Fumigation Service and Supply Inc., and its sister company, Insects Ltd, took the lead in trials and the commercial adoption of alternatives for commodities such as grains and structures, e.g. food processing plants and flour mills.

- The Canadian government has strongly encouraged Canadian companies to take a leadership role in the development and adoption of alternatives. For example, many individual strawberry farmers switched to alternatives. Of particular note has also been the contribution of individual member companies of the Canadian Pest Control Association and the Food and Grocery Products Manufacturers. These companies participated in joint demonstration projects aimed at testing the effectiveness of alternative techniques to MB fumigation in structures. Working co-operatively, they implemented complex IPM procedures that eliminated and/or greatly reduced their need for MB (Environment Canada 1995, Agriculture and Agri-Food Canada 1996, Stanbridge 2002ab).

- The Association of Harvesters and Exporters of Fruit and Vegetables in Almería (COEXPHAL) has 25 years of experience in the intensive production of tomato, watermelon and other fruit and vegetables. The region produces and exports 70% of the vegetables in Spain, and used MB on about 1430 hectares in 1995. COEXPHAL was the driving force behind the development of environmental quality standards for vegetable production (Norm UNE 155001) in 1997, which *inter alia* obliged growers to use MB alternatives. As a result MB has been virtually eliminated in Almería by the adoption of alternatives, and the produce is entirely acceptable to customers (Fernández 2002).

3.6.3.3 Supermarket policies on MB in agriculture

Supermarkets purchase large quantities of fruit and vegetables from around the world. Several supermarket companies have adopted policies on MB, for example:

- Sainsbury's, a major supermarket in the UK, reported that some of its contracts with suppliers specifically prevent the use of MB. Under the programme supporting IPM implemented by Sainsbury's, the use of MB is not permitted for certain crops and for all other crops ‘use is being reduced as much as possible as soon as possible…’ (Prospect 1997).
- The Co-op supermarket chain, which owns a number of farms in the UK, reported that they banned the use of MB as a soil fumigant on their own farms in the mid-1990s (Prospect 1997). In July 2001, Co-op announced a new code of practice, developed with suppliers, which will prohibit 24 pesticides including MB, as a result of rising consumer concerns about health and environmental impacts (Buffin 2001a).
- Another UK supermarket, Marks and Spencer, announced in 2001 a plan requiring its suppliers around the world to reduce and phase out the use of 79 pesticides that pose risks to health or the environment; MB is included in this list (Buffin 2001b).
- In Sweden, several supermarkets have contacted suppliers of canned tomatoes in Italy, to ascertain whether MB was used when growing the tomatoes (C. Berkow, *pers.comm.*).

Many European supermarkets are requiring their suppliers and farmers around the world to adopt integrated pest management (IPM) and environmental certification systems. The supermarkets have established a set of standards on ‘Good Agricultural Practice’ in horticultural production, called EUREP-GAP (FoodPlus 2001). The supermarkets will require fruit and vegetables to be grown under certified EUREP-GAP standards, or equivalent standards, by the end of 2003. The standards require growers to provide written justification if MB or other fumigants have been used, and farmers have to demonstrate that they have assessed alternatives (Moeller 2002). The EUREP compliance criteria do not allow pesticides that are banned in the EU. As a result, farmers outside the EU who want to export to EUREP supermarkets will not be able to use MB when it is phased out by the EU (FoodPlus 2001).

3.6.3.4 Policies of manufacturers, traders and auction houses

Companies manufacturing food and tobacco products, wholesalers, auction houses and other trading companies often set conditions or specifications for product quality and other parameters in contracts. Grain importers, for example, sometimes specify in commercial contracts that grain must be treated with MB before shipment. In several cases, manufacturers or traders have now ruled out the use of MB.

Some European tobacco companies have informed tobacco producers in Zimbabwe that they will no longer accept post-harvest or pre-shipment treatments with MB. This is because MB can adversely affect the quality of tobacco and because of its environmental effects. Some tobacco companies purchasing tobacco from Asian producers have also stated that they do not want tobacco to be treated with MB in storage or prior to shipment (UNDP 1995). Phosphine is now the predominant fumigant for postharvest tobacco.

An international environmental certification programme called Milieu Programma Sierteelt (MPS) has been established by major flower auction houses in the Netherlands in response to consumer concerns about agricultural production methods. Growers who wish to be certified have to produce flowers according to the MPS standards on pesticide use, water and energy. The MPS standard prohibits the use of certain highly toxic chemicals, and MB cannot normally be used in the production of MPS certified flowers. More than 4,800 farmers implement the MPS programme in 22 countries, including Belgium, Canada, Costa Rica, Ecuador, France, Israel, Italy, Kenya, Netherlands, South Africa, Tanzania, Uganda, USA, Zambia and Zimbabwe (T. de Groot *pers. comm.*).

3.6.3.5 Eco-labelling and product information

A number of countries, including developing countries, have initiated eco-labelling or environmental labelling programmes for refrigerators and other products that utilise ODS. Factual labelling allows purchasers to select products with fewer environmental impacts if they wish, enabling consumers and the market to express preferences. For example, under the Clean Air Act in the USA, products manufactured with CFCs and other ODS, with the exception of MB, are required to carry a special consumer label which reads "Warning: manufactured with [name of ODS], a substance which harms public health and environment by destroying ozone in the upper atmosphere" (Clean Air Act section 611).

Under Decision VII/29, TEAP analysed the role of eco-labelling in relation to MB, noting that 'The purchasing decisions of consumers can also be influenced by product information on the environment which in turn affects production, use and disposal of specific products. Eco-labelling systems are widely used. Those Parties that are not yet using Eco-labelling systems to promote the objectives of the Montreal Protocol might consider the benefits of adding such a market-based measure to their ozone protection policies.' (TEAP 1997).

Consumer and environmental organisations in several regions have requested labelling of products so that purchasers can exercise a choice with respect to MB. For example, the Food Commission, a consumer advocacy group in the UK, has asked supermarkets to label fruit and other produce: 'Grown without the use of Methyl Bromide'. The Commission reports that it has requested labelling so that customers can choose environmentally-friendly fruit (Food Commission 1997). In the USA, Friends of the Earth, the Natural Resources Defence Council, Pesticides Action Network and other organisations have requested labelling of products produced with or without MB (NRDC *et al*. 1993, MBAN 1995). The Jordan-GTZ agricultural IPM project developed a certified label for IPM products and products grown without the use of MB. When the MB labels were trialled on packs of fresh strawberries exported to supermarkets in Europe the retailer gave positive feedback and encouraged the producer to continue labelling products in this way (Hasse 2001).

3.6.4 Levies and taxes on methyl bromide

In some countries levies or taxes have been placed on ODS and pesticides for environmental purposes, such as raising revenue for the development of alternatives and raising prices of environmentally damaging activities to encourage users to adopt alternatives. Several governments have introduced such taxes as a step towards implementing the 'polluter pays' principle.

3.6.4.1 Example of voluntary levy on MB

In 1995 MB users in Australia decided to introduce a levy of about $A0.20 per kilogram of MB imported. The levy was changed to $A0.30 per kg from 2001. The levy is collected at wholesale level by the importers. In 1998 it raised approximately $A250,000 which was matched by funds from the national Horticultural Development Corporation, giving about $A500,000 for research and demonstration, in addition to funds specifically for communication about alternatives to farmers (Porter 2002). In addition, the increased prices made alternatives more attractive for commercial use and increased grower acceptance of the need for research.

3.6.4.2 Taxes on ODS chemicals

The Czech Republic's Ozone Protection Legislation (1995) placed a tax on producers and importers of ozone depleting substances. The revenue is used by the State Environmental Fund for ozone protection. From January 1996 the tax was applied to MB (Parliament of the Czech Republic 1995).

Regulations in Slovakia placed a fee on all imports of ODS. As a result, the price of MB became higher and encouraged users to adopt alternatives. Poland established a fee on the emission of pollutants to the atmosphere ($US0.02 per kg), which was intended to act as a disincentive to the use of pollutants like MB (Slusarski 2002).

From 1996, Environment Australia (formerly the Environmental Protection Agency) required MB importers to purchase import licences at a cost of $A10,000 for each two-year period. In addition, Environment Australia charges an activity fee of $A90 per tonne of imported MB. The activity fees are held in a fund used to support research for phasing out MB and other ODS.

Some countries have placed taxes and levies on pesticides in general, providing other models. In Sweden, an environmental levy of approximately $US1.50 per kg of active pesticide ingredient raised about US$3 million per year for research and extension in non-chemical and IPM methods (Watts 1996). Denmark also placed an environmental tax on pesticides as a ‘polluter pays’ measure, raising about $US40 million in 1996 for environmental programmes and research on non-chemical techniques (Agrow 1995). India placed an 18% duty on imports of most pesticides (UNEP 1999).

3.6.4.3 Taxes on products

TEAP notes the following point about potential domestic taxes relating to products that use MB:

> ‘The market prices of goods produced using MB could be driven up to discourage demand by imposing specific product taxes. Such measures would require a means of differentiating between products which have been produced or treated with MB and those that have not and a certification process for the proper implementation of a tax.’ (TEAP 1997).

Certification systems for food products are in existence and examples can be found in the international and national certification procedures for organic food products. MBTOC is not aware of any cases where taxes or levies have been placed on products grown using MB.

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Chapter

4

Alternatives to methyl bromide for soil treatment

4.1 Introduction

The 1998 MBTOC Assessment identified a wide range of methods that under particular circumstances could act individually or in combination to replace or reduce the need for MB treatments of soils. In many cases at this time, adoption of technologies was restricted by inconsistency of treatments and lack of confidence that an alternative would provide consistent long term control. Since 1998, however, clearer trends are developing on those technologies which can be adopted to replace MB fumigation without loss of crop yield or quality in crops where MB was once regarded to be irreplaceable. Most significant are those studies that have concentrated on measurements of the effects on target pests and weeds in addition to measuring effects on yields and crop quality (Minuto *et al.* 2000, Tjamos *et al.* 2000, Vannacci and Gullino, 2000).

Since then research has concentrated on improvements in the variation in the efficacy of alternatives against target pests and weeds compared to MB. This chapter discusses not only the importance of these new findings, but also the most likely alternatives to replace MB and new products which are now being considered as potential useful alternatives.

MBTOC recognises the importance of finding alternatives that offer both 'in-kind' replacements to MB and long term sustainable crop protection methods. For this reason, several alternatives discussed in the 1998 MBTOC Report (e.g. anhydrous ammonia) are no longer considered as alternatives and are no longer discussed. It is recognised that there are a large number of chemical and non-chemical technologies that can replace MB fumigation in specific crops and situations and that one technology suitable in one part of the world may or may not always suit another.

MBTOC recognizes that, with very few exceptions, most crops can be grown without MB. However, legislative regulations, costs and other factors limit the practical availability of alternatives for all crops in all places. Significant investment in research and development, and in technology transfer will be necessary to successfully implement alternative pest management systems world-wide. In spite of the development of many effective alternatives, their adoption will also be affected by factors such as pest pressure, soil type and climate.

4.2 Adoption of Alternatives

On January 1 2001, a 50% reduction in the consumption of methyl bromide, agreed to by Parties to the Montreal Protocol, became effective. This has led to the adoption of a range of alternative strategies. To date, most of the reduction in MB use has been obtained by the adoption of formulations of MB/chloropicrin (PIC) containing lower concentrations of methyl bromide and reductions in the rate applied per unit area of land. In the EU, mandatory use of impermeable barrier films in several countries (e.g. France) has led to a 50% reduction in the rate of product applied.

The 50% reduction in MB use in regulated countries has also been assisted by the adoption of chemical and non chemical alternatives. The relative uptake of technologies, however, has varied between countries and is dependent on cost, availability and registration issues associated with the particular alternatives.

Dramatic increases in the cost of MB since the last report (100 – 400% in 4 years) have contributed to the adoption of alternatives and new crop rotation practices in certain countries. For instance, some large tomato growers in Australia have avoided the use of MB fumigation by adoption of new crop rotation practices with sugar cane and other crops. Also, MB is no longer available for vegetable growers on the central coast of Western Australia due to high costs, and they now use other soil disinfestation practices instead (dazomet, metham sodium and the recently registered, 1,3-dichloropropene (1,3-D) (Anon.2001a).

In Japan, a reduction of 35% of the baseline MB usage has been achieved across a range of crops (cucurbits, tomato, peppers, strawberries, ornamentals) by the adoption of alternative chemical fumigants (1,3-D, dazomet and PIC). This has been assisted by the development of a range of new novel application methods (Tateya, 2002). In Costa Rica, solarisation has replaced MB usage on approximately 500 ha of melon production (10% of total production) as the method ideally suits the crop rotation and climatic conditions (Chaverri and Gadea 2002). In California, most of the reduction from the baseline MB usage has been achieved by uptake of MB/PIC formulations with lower concentrations of MB or a switch to 1,3-D to control nematodes for perennial fruit and nut groves. In Morocco, grafting and plant resistance used in combination with metham sodium is widely used to control various soilborne pathogens of vegetables, particularly root knot nematode (Besri 2002).

4.3 Transitional Strategies to Reduce MB Dosages

Since 1998, MB dosage reductions for preplant soil fumigation and fumigation less frequently have been a major factor enabling countries to satisfy the commitments for MB reductions under the Montreal Protocol (Lopez-Aranda *et al*. 1999, Porter *et al*. 1999).

In regions where MB has been traditionally applied by hot or cold gas injection at high rates at or above 100 g m^{-2}, MB dose rate reductions have primarily occurred by the adoption of lower rates of 40 to 60 g m^{-2}. More recently, even further reductions of up to 50% i.e. 20-30 g m^{-2}, have been possible by adoption of virtually impermeable barrier films (VIF) (Minuto *et al*. 1999a, Melgarejo *et al.* 2001, Noling *et al.* 2001) or by combining solarisation with fumigation (Besri 2002, Haidar and Sidahmed 2000, Medina-Minguez, 2000, Bello *et al.* 2002). In regions where fumigation was previously achieved by MB/PIC mixtures (98:2, 70:30, 67:33) injected into soil, dosage rate reductions have mainly been achieved by using mixtures containing even lower concentrations of MB/PIC (50:50, 33:67). In these regions, barrier films such as VIF have been less effective because lower rates (30-40 g m^{-3}) of MB/PIC mixtures have already been adopted (Lopez-Aranda *et al*. 2002). Further information on VIF film, and minimum standards of film set in some countries, is provided in Section 8.3.

MB/PIC mixtures with lower rates of MB (30:70) have the added benefit that they have provided excellent control of fungal pathogens and have produced yields which are equivalent or significantly higher (14%) for crops than mixtures with higher ratios (98:2 and 70:30) (Porter *et al*. 1998). These low MB ratio mixtures, however, have the disadvantage that they are less effective for control of weeds, although this has been overcome in some areas by the incorporation of herbicides (Fennimore and Richard 1999, Gilreath *et al.* 1999).

Once the 70% reduction step for MB occurs in 2003, transitional strategies will only have limited potential to offer an alternative as sources of MB become scarce. Growers will be forced to adopt alternative chemical or non-chemical treatments.

4.4 Alternatives which Replace MB for Soil Disinfestation

4.4.1 Chemical alternatives

Since the 1998 MBTOC report there have been some major advances in development of chemical alternatives to methyl bromide, particularly, data that demonstrates improved consistency of alternatives for control of target pests. Several chemical products are under development, e.g. sodium azide, propylene oxide. For some specific pests, single chemical alternatives can be used. However, for pest complexes, combinations of chemicals and/or other pest control methods will usually be necessary.

Two groups of chemicals appear to be the best ‘in-kind’ alternatives to methyl bromide and thus have the potential to achieve broad spectrum control of pests, pathogens and weed seeds. The first group are the fumigants. Fumigants are volatile chemicals, which under typical field conditions, exist as gases or are converted into gases. Some fumigants are injected directly into the soil as liquids or gasses (e.g. 1,3-D, MB and chloropicrin). The other group of alternatives are not true fumigants, but they release the fumigant methyl isothiocyanate (MITC) after application in the soil. For example, when the liquid formulation of metham sodium is applied to soil, it converts to MITC in solution and then finally, as chemical conversion continues, to MITC in a gas state before further breakdown. Non-fumigant chemicals also include non-volatile pesticides, which kill target pests either by contact action (e.g. Ethoprop) or systemic action (e.g. aldicarb, oxamyl, fenamiphos, fosthiazate and cadusafos).

Some combinations of chemicals are as effective as MB, while others are only effective if they are utilised as part of an integrated crop management. These systems include combinations of chemicals (e.g. fumigants, soil applied nematicides, fungicides) and non-chemical methods and strategies (crop rotation, resistant varieties, solarisation). Several studies have demonstrated that some fumigants used alone or as mixtures provide pest control and yield increases approximately equivalent to that obtained with MB (Duniway *et al.* 1999, 2001, Locascio *et al.* 1999, Porter *et al.* 1999, 2002, Nelson *et al.* 2001, Lopez-Aranda *et al.* 2002, Mattner *et al.* 2001).

New chemicals, e.g. methyl iodide and other iodinated compounds, propargyl bromide, and sodium azide, have been reported to provide a similar efficacy to MB and have potential to be single chemical replacements for MB, but require trialling on a commercial scale to identify any long term effects of treatments (Yates and Gan 1998, Hutchinson *et al.* 1999, Appel and Rodriguez-Kabana 1999, Ajwa *et al.* 2001a).

Factors affecting acceptance of chemical alternatives include registration status, local availability, costs, new application technologies, labour requirements and efficacy against target pests. Depth of penetration in soil, poor dispersion of chemicals under various conditions and narrow effective temperature ranges may affect efficacy. As with MB, use of chemical alternatives may have human health and environmental consequences, which must be taken into consideration. Regulatory actions within each country may limit the availability of an alternative chemical in specific geographical areas.

It is important to note that, in many cases, studies conducted to date were performed in fields where the composition of pests and resultant pest pressures reflect the consequences of repeated methyl bromide fumigation. Future studies on alternatives need to consider performance both in soils with and without a history of fumigation with MB and areas with high pest pressures.

4.4.1.1 Chloropicrin (trichloronitromethane)

Chloropicrin is a liquid fumigant (boiling point: 112°C) which is injected into soil under plastic. It is a severe lachrymator and requires careful handling. It is normally applied at rates of (10 – 15 g m^{-2}) when used as a component of a mixture with MB. Higher rates (15 - 50 g m^{-2}) are being used effectively when the product is applied alone. PIC has been shown to be more effective than MB for control of soil-borne fungi (Desmarchelier 1998) and some insects (Wilhelm and Westerlund 1994). It is a weak nematicide and has limited herbicidal activity, although it can kill some germinated weed seeds (Porter *et al.* 2002). Higher rates have been shown to give greater nematicidal activity (Taylor and McBeth 1941), but there is a lack of information from recent trials. There is now wide acceptance that in areas where weed and nematode pressures are low, chloropicrin alone is as effective as MB for control of fungal pathogens (Locascio *et al.* 1999, Porter *et al.* 1999) and for improved growth and yield responses (Nelson *et al.* 2001, Norton 2001, Trout *et al.* 2001).

Specifically, PIC has been very effective against major soilborne fungi, (e.g. *Verticillium dahliae, Phytophthora fragariae)* of strawberries in California, Florida and Australia (Winterbottom *et al.* 1999, Porter *et al.* 1999, Donohoe *et al.* 2001, Duniway *et al*. 2001). New formulations of chloropicrin are providing alternative methods of application. For instance, emulsifiable concentrate (EC) formulations have shown potential for MB replacement in California (Ajwa *et al*. 2002). Also encapsulating around either chloropicrin tablets or chloropicrin tape in a water-soluble film is proving effective for control of a wide range of soil pests in Japan (Tateya 2002).

Plant back periods for chloropicrin have been shown to be similar to MB despite concerns over longer plant back times at low soil temperatures (Porter *et al.* 2000). Also research is still needed to determine effective and economical application rates and the long term effects of chloropicrin when applied alone. Owing to the noxious nature of chloropicrin, extreme care must be taken to ensure proper sealing after application.

Owing to its excellent effectiveness against fungal pathogens, chloropicrin is the main component of most of the fumigant mixtures being adopted as an alternative to methyl bromide.

Some countries do not permit use of chloropicrin.

4.4.1.2 1,3-Dichloropropene

1,3-dichloropropene (1,3-D) is a liquid fumigant (boiling point: 104-112°C). It is highly effective against nematodes. At rates of (35-50 g m^{-2}) it also provides effective control of insects and suppresses some weeds and pathogenic fungi (Aguirre 1997, 1998, Gonzalez and Pedreño 1997, Noling and Becker 1994, Raski and Goheen 1988, Soler 1997, Hafez and Sundararaj 2001). 1,3-D alone is used as a fumigant nematicide in cropping systems where the important target pests are nematodes (e.g. pineapples). Mixtures combined with chloropicrin are presently the main fumigant systems being adopted as alternatives for methyl bromide in most developed countries (see Section 4.4.4.1 and Eger and Peterson 1999).

Research with EC formulations suggests the possibility of the practical application of 1,3-D where shank applications are not feasible (i.e. fine textured soils). The spectrum of activity of new emulsifiable concentrate (EC) formulations has been improved by combination with other fumigants and new methods of application (Lopez Robles and Martinez Pena 1998, Soler 1997, Visbec 1998, Norton 2001, 2002).

A possible disadvantage of 1,3-D is that it has been shown to be subject to accelerated degradation by soil micro-organisms in a few studies (Ou 1998). However, the practical significance of this phenomenon is unclear (Leistra 1972, Ou 1998).

Present regulations on 1,3-dichloropropene on area quotas, buffer zones and personal protective equipment are currently under review in USA and registrants are conducting research to reduce the impact of the regulations on use of this material (Houtman 2000).

4.4.1.3 Methyl isothiocyanate (MITC) and MITC generators

MITC and compounds that generate MITC (dazomet, metham sodium, metham potassium) are highly effective for controlling a wide range of arthropods, soil-borne fungi, nematodes and weeds, but are less effective against bacteria. The liquid MITC fumigants have a boiling point of approximately 100°C. When incorporated into soil with adequate moisture, MITC generators produce methyl isothiocyanate.

Inconsistent control has been the major factor affecting the adoption of the MITC generators as a replacement for MB (Locascio *et al.* 1999, Shaw and Larson 1999). Recent research has shown that more consistent results can be obtained by using application techniques which provide a more uniform distribution of the fumigant in soil and tarping to reduce vapour loss (Haglund 1999, McKenry 2001).

Studies have shown that shank injection of metham sodium, a liquid MITC generator, in bands to soil does not provide consistent efficacy due to non-uniform distribution in the soil. It does not disperse well and requires water for good movement and efficacy (Ajwa *et al.* 2001b).

The high water-solubility of metham sodium makes it suitable for application to soil via irrigation systems such as overhead sprinklers, injection or drip irrigation under plastic. However, application through overhead sprinklers, although effective, has been prohibited or severely regulated in many countries. Application through drip application has been successfully used for control of weeds, fungi and nematodes in many crops and regions including Morocco, Spain, Southern France, Israel, Italy and the USA (Laita 1997, Nakano and Botton 1997, Pocino 1997ab, 1998, Rabasse 1998, Tió 1998, Yabase 1997, McMillan and Bryan 1999, Csinos *et al.* 2000).

Dazomet is a granular MITC generator. It requires uniform distribution in soil by mechanical means and adequate soil moisture for good movement and efficacy. Under these conditions, studies have shown that at rates of (35–50 g m^{-2}) it can also provide equivalent or better control than metham sodium (Locascio *et al.* 1999, Lopez-Aranda *et al.* 2002). It gives satisfactory control of weeds, nematodes and fungi in Argentina, Australia, Europe and Japan where it is well known. Also, because dazomet is a granular formulation it is easier to apply than some of the other fumigants for small scale applications where machinery is difficult to use.

A disadvantage of the MITC generators is that they have long residue times in the soil and this has resulted in phytotoxicity. Therefore longer plantback periods than for MB may be required before some crops (e.g. strawberries, tomatoes, melons, cut flowers) can be replanted, especially in cool conditions (Ajwa *et al*., 2001a, Porter *et al.* 2000). Another isothiocyanate ester, allyl isothiocyanate, recently tested in Italy and USA, shows similar results to MITC generated from metham sodium (Minuto *et al.* 1999b, Rodriguez-Kabana 2000).

Recent reports demonstrating biodegradation of compounds containing MITC after repeat application to soil are creating concerns about acceptance of these products as alternatives to MB (Thomson 1992, Wharton and Matthiessen 2000, DiPrimo *et al.* 2001).

Metham ammonium is used on a small scale in Japan and Argentina as a MITC generator. However these uses are not at present replacing the use of methyl bromide significantly (Tateya 2002).

When combined with chloropicrin and when tarps are used, the performance of MITC and dazomet have shown similar efficacy to MB (Porter *et al.* 1999, Minuto *et al.* 1999a). Presently, mixtures of these products are not available due to difficulties (chemical incompatibility) with combining the products. However, machinery has been developed which now allows injection of metham sodium and chloropicrin independently without contact during application (Porter *et al.* 2002).

4.4.2 Chemical alternatives that require further development

4.4.2.1 Methyl iodide and other iodinated compounds

Methyl iodide, (MI) or iodomethane, is a liquid pre-plant soil chemical with a boiling point of 42°C. Since the 1998 report, methyl iodide has been tested on a wider range of crops and at rates of 35 – 50 g m^{-2} continue to demonstrate efficacy equivalent to MB (Hutchinson *et al.* 1999, Schneider *et al.* 2001ab, Zhang *et al.* 1998, Becker *et al*. 1998). Studies indicate that methyl iodide is as effective as or more effective than methyl bromide to control a wide variety of soil-borne pathogenic fungi, nematodes, and weeds (Becker *et al.* 1997, 1998, Ohr *et al*. 1996ab, Zhang *et al.* 1997, 1998, Schneider *et al.* 2001ab). VIF tarps can decrease methyl iodide volatilization (Gan *et al.* 1997). The ozone-depleting potential of methyl iodide is very low because the molecule is broken down by photolysis in the troposphere (Ohr *et al.*, 1996a). MI is considerably less volatile than MB (b. p. -4°C).

Methyl iodide is a promising, potential “drop in” replacement for MB and is receiving more interest now that a commercial partner has been found for the US (Allan and Schiller 2000).

MI has also proven effective when applied through a drip irrigation system (Sims and Stranghellini 2000, Schneider *et al*. 2001b). Registration is currently being sought in several countries. Current indications are that the cost of this product may be high for many crops for which MB has formerly been used.

4.4.2.2 Iodinated hydrocarbon fumigants.

The potential for other iodinated hydrocarbons to replace MB for nematode and weed control has recently been demonstrated (Rodriguez-Kabana 2000).

Recent work demonstrated that iodinated hydrocarbons are not only more effective than bromo- or chloro- compounds for control of plant pathogenic nematodes, but also possess considerable herbicidal and insecticidal properties. Specifically, on a dosage basis, methyl iodide is more nematicidal than methyl bromide. Also, the nematicidal and herbicidal activities of iodohydrocarbon fumigants increase with the number of carbons and iodination of the hydrocarbon molecule (Rodriguez-Kabana and Appel 1999). Highest activities correspond to 1,2-diiodoethane, 1,3-diiodopropane and 1,4-diiodobutane (Appel and Rodriguez-Kabana 1999). These iodo compounds also exhibit outstanding insecticidal properties. In contrast, monoiodo compounds are most nematicidal (Appel and Rodriguez-Kabana 1999). The nematicidal and herbicidal properties of 1,3-diiodopropane exceed those of dibromochloropropane (DBCP), once considered the best fumigant nematicide. Diiodo hydrocarbon fumigants have not been explored for practical use but may be excellent substitutes for methyl bromide in the fumigation of soils. There is some evidence that diiodo compounds can control fusarium wilt.

4.4.2.3 Other iodinated compounds

Iodine is the most microbiocidal of all the halogen elements. It has been used in medicine since the 19th century as a general "germicide" and in the preparation of antiseptic formulations. Its use in agriculture has been limited because of high cost in comparison with Br or Cl. Applications of aqueous I_2-KI solutions have little effects on nematodes and other soil-borne pathogens and result in severe phytotoxicity (Rodriguez-Kabana and Appel 1999). However, the use of colloidal iodine, stabilized with a suitable "protecting" colloid has been used as an antihelmintic in poultry production (Merck Index 1989). Since the last report a new formulation of elemental iodine has been tested extensively in the U.S. and Chile as an alternative to methyl bromide with promising results for control of weeds, nematodes and other soilborne pests (Adams *et al*. 2001, Adams *et al.* 2000, Kokalis-Burelle *et al.* 2000). Severe phytotoxicity has been observed in several crops in trials with the new formulation (Nelson *et al.* 2001)

4.4.2.4 Propargyl bromide

Propargyl Bromide (3-bromo-1-propyne, $BrCH_2CCH$) is a heavy, volatile liquid (b.p. 88-90°C). The compound is unstable and requires a stabilizing agent for safe handling. It was used in the 1960's to enhance the performance of chloropicrin and MB in a product called TRIZONE (60% MB, 30% chloropicrin, 9% propargyl bromide). TRIZONE controlled a wide range of soil-borne pests, but was discontinued in 1968. Recent studies in the U.S. with propargyl bromide stabilized with toluene confirmed its broad range of activities against weeds, nematodes and other soil-borne pests (Trout, 2001, Noling *et al.*2001, Schneider *et al.* 2001a, Elmore *et al.* 2001). Applications through drip irrigation in horticultural crops resulted in increased yield and pest control equivalent to those obtained with MB-chloropicrin mixtures. Detailed dosimetric studies indicated that propargyl bromide is considerably less nematicidal than other halogenated hydrocarbons (e.g. ethylene dibromide) and that rates in excess of 90 kg ha^{-1} are required to obtain acceptable nematicidal and herbicidal activities (Rodriguez-Kabana 2000a). At present further development of the compound appears limited because of the lack of an environmentally acceptable stabilizing agent.

Relatively high rates of application and tarping may be required for effectiveness equivalent to MB (Rodriguez-Kabana 2000a). Trials with propargyl bromide on tomatoes in Florida and strawberries in California have given good control of nutsedge and *Meloidogyne incognita* (Noling *et al.* 2000). Applications have been made both by shank and drip irrigation (Trout 2001, Schneider *et al.* 2001a). Further it was found that strawberry yields from drip fumigation were greater than yields from shank injection (Ajwa *et al.* 2001a).

4.4.2.5 Inorganic azides.

Na and K azides are salts of hydrazoic acid (HN_3) that have been explored in a limited manner for their pest controlling properties in the past. These materials are solids, readily soluble in water, and can be formulated as granules or liquids. Information on the toxicological properties of sodium and potassium azides on humans is available (TOXLINE, 2001). These compounds are hypotensors (Merck Index, 1989) and were used in the 1950's for treatment of certain types of cancers in humans and more recently in formulations to fight AIDS. Extensive studies have demonstrated that azides are not carcinogenic. Sodium azide is currently being trialled as an MB replacement in the US. It has been particularly effective against purple and yellow nutsedge, and other weeds difficult to control with MB, such as Carolina geranium and burr clover (*Medicago* spp.) (Rodriguez-Kabana 2001b). Initial studies have shown sodium azide to provide equivalent efficacy to MB for target pests and weeds in certain annual crops (vegetable and some ornamentals).

Na and K azides when added to soils ($pH<7.0$) release HN_3 which is converted chemically by reaction with water to NH_4^+ and to nitrate through the action of nitrifying bacteria. (Parochetti and Warren 1970). Field research in the 1970's in a commercial pine nursery and with several row crops showed that granular formulations of Na and K azides applied to soil have broad spectrum activity against weeds, nematodes, and soil-borne phytopathogenic fungi (Kelley and Rodríguez-Kábana 1979b, Rodríguez-Kábana and Robertson 2000, Rodríguez-Kábana *et al.* 1975, Rodríguez-Kábana *et al.* 1972). Similar results have been obtained in other areas of the U.S. and in Belgium with high-value horticultural crops (van Wambeke *et al.* 1984, 1985, van Wambeke and van den Abeele 1983). Microbiological studies of soils treated with Na azide for several years indicated that, in contrast to MB-fumigated soils, those treated with azide showed increased population levels of a group of fungi (principally species of *Trichoderma* and *Gliocladium*) antagonistic to a broad spectrum of soilborne phytopathogenic fungi (Kelley and Rodríguez-Kábana 1979a, 1981). The mode of action of Na and K azides on soil-borne pathogens is based on short-term direct toxicity, but may also involve long-term effects through enrichment of the soil with microbial species antagonistic to the pathogens. Azides are more effective in annual crops when the soil is covered after application (Rodriguez-Kabana, 2002).

Sodium and K azides can be formulated as granules (attapulgite clay, diatomaceous earth) or in a variety of liquid formulations (Rodriguez-Kabana 2001b, Rodriguez-Kabana 2000abc). Key to the stability of these formulations is that pH remains greater than 9.0. This can be accomplished for granular formulations by including sufficient Na or K carbonate to buffer the granules at pH 9.5 - 10.0. Granular formulations were used to control weeds and soil-borne pests typically located in the top 7 - 10 cm of the soil profile (Parochetti and Warren 1970, Rodríguez-Kábana *et al.* 1972). However, for other pests (nematodes, *Armillaria, Verticillium*) and deep-rooted crops (grapes, fruit, and nut trees), liquid formulations are more suitable (Rodriguez-Kabana 2000abc).

Historically, a limitation to the use of azides has been the ability of formation of explosive azides. While azides of heavy metals, such as Cu, Pb, Hg, are unstable and explosive, those of Na and K are considered stable under ordinary conditions (Moeller, 1952), but may react to give explosive compounds under some conditions. The advent of stabilised aqueous formulations has eliminated this risk. Sodium azide has the advantage that it can be delivered through irrigation water and does not need special equipment for application. Trials to support registration in the US are proceeding in California and Florida.

4.4.2.6 Propylene oxide

Propylene oxide is a flammable, colorless, ethereal liquid, soluble in water (40.5% by weight, 20^0C), miscible with alcohol, ether and other like solvents. Propylene oxide (PO), like ethylene oxide (CH_2OCH_3), has been used for laboratory and small scale fumigation of soils and other materials, such as food stuffs and microbiological nutrient media (Dhingra and Sinclair 1985, Hansen and Snyder 1947, Tuite 1969, Thompson and Gerdemann 1962, Warren 2001). In contrast with ethylene oxide, the liquid nature of PO at ordinary atmospheric pressure and temperatures, simplifies its use as a fumigant. PO is a broad-spectrum nematotoxic compound, active against root-knot (*Meloidogyne* spp.), reniform (*Rotylenchulus reniformis*), cyst (*Heterodera* spp.) and many other important ecto- and endo-parasitic nematodes (Noling *et al.* 2001, Rodriguez-Kabana 2001d).

PO is being investigated as a potential in-kind replacement for MB, but results have been inconsistent. Moisture content of the soil is critical for efficacy. Recent experiments have demonstrated that PO is herbicidal against a wide variety of important broadleaf and grass weed species, including nutgrasses (*Cyperus* spp.), pigweed (*Amaranthus* spp.), Jimson weed (*Datura stramonium*), common bermudagrass (*Cynodon dactylon*) and other weeds difficult to control. PO injected directly into soil is effective in controlling phytopathogenic nematodes, and weeds at rates of 280-570 L ha^{-1}; drenching soil with aqueous solutions of PO is less effective than direct injection of the chemical for control of soil-borne pests (Rodriguez-Kabana 2002ab). Results from recent strawberry field experiments in the U.S. indicate that PO is as effective as mixtures of MB/PIC, and other fumigants, for control of root damaging pests (Rodriguez-Kabana, R. *personal communication)*.

4.4.2.7 Sulphuryl fluoride, carbonyl sulphide, cyanogen

Since the last report, research indicates that several new chemicals may have potential as MB alternatives for soil treatments. Sulphuryl fluoride (Cao *et al*. 2002), carbonyl sulphide (Ren *et al.* 2001), dimethyl disulphide (Fritsch *et al.* 2002) and cyanogens have been trialled but there is little efficacy data and at this stage these chemicals need further development before being considered as alternatives for MB.

4.4.2.8 Other chemicals

Some chemicals have activity against specific pests for which MB may have been used. These chemicals have the potential to be important components of pest management systems which replace MB. Examples are calcium cyanamide and the nematicides, avermectin (China), fosthiazate and oxamyl (Japan and other countries).

Formaldehyde. A formulation of formaldehyde has been shown to provide effective broad-spectrum control of soil-borne pathogens without the previously reported phytotoxicity (Kritzman *et al.* 1999). However, since the last report, no progress known to MBTOC has been made toward developing formaldehyde as an alternative for MB.

Furfuraldehyde is a volatile liquid compound found in a variety of foodstuffs, e.g., bread and other bakery products, beer, spirits, coffee. It is considered non-toxic to humans. Furfuraldehyde alone, and in combination with mustard oils, or naturally occurring isothiocyanates, is effective for the management of weeds, insects, nematodes and other soilborne pathogens (Rodríguez-Kábana 2000, Rodríguez-Kábana *et al.* 1993, Rodríguez-Kábana and Walters 1992). Data from recent studies indicate that furfural-based biofumigants while very active against phytopathogenic nematodes have no deleterious effects against beneficial microbivorous nematodes (Rodríguez-Kábana 2002). Furfural-based biofumigants have herbicidal activities against most common weeds but must be applied at high rates > 500 kg a.i./ha for broadspectrum activity against soil-borne plant pests. A number of emulsifiable formulations of these biofumigants have been developed for application through drip-type irrigation systems and are currently being tested as substitutes for MB.

Other synthetic versions of compounds that occur in nature can be potential alternatives to MB for some pests. There are a number of plant species that have relatively few problems caused by soil-borne pests. Some of these plants, e.g. brassicas, mustards, radishes, have been used as rotational crops to suppress nematodes and soil-borne fungal pathogens. Cruciferous plants produce a variety of mustard oils some of which are very active against plant pests (Gamliel and Stapleton 1993); other plant species, e.g. oregano, thyme, lemon grass, produce simple volatile monoterpenes, terpenoids, and aromatic compounds with considerable activity against phytopathogenic fungi, nematodes and other soil-borne plant pests. As with furfuraldehyde, some of these compounds are produced commercially on a large scale. They include benzaldehyde, citral and cinnamaldehyde (Harborne and Baxter 1993, Grainge and Ahmed 1988). Research on the nematicidal and microbiocidal properties of these volatile, naturally occurring compounds has shown promise for development of new management strategies for nematodes and other soilborne plant pathogens (Soler-Serratosa 1993, Soler-Serratosa *et al.* 1996).

Ozone. Although ozone has been shown to increase tomato yields above untreated controls, the response is not attributed to disease control and therefore more research is required to determine if it is an alternative to MB (Pryor 1999). Since the last report, no progress known to MBTOC has been made toward developing ozone as an alternative for MB.

Sodium tetrathiocarbonate. This product, Enzone, is a water soluble salt formulated compound stabilised in concentrated aqueous solutions which decomposes in soil to release carbon disulphide (CS_2) (Young 1990). It is registered for commercial use in France and Spain and for a wide range of nematodes in orchards and vines in California and orchard and vine replant problems (R. Keigwin, pers. comm.). Drip applied applications have failed to give good control of nematodes in tomatoes in Florida (Locascio *et al.* 1997). Other studies have also given inconsistent control of nematodes and it has yet to be demonstrated on its own as an effective alternative to MB in many situations.

It is more effective against nematode and insect pests, but not weeds or other soilborne pathogens. Performance of sodium tetrathiocarbamate was equivalent to MB in control of a root rot fungus of almond trees (Adaskaveg *et al.* 1999). In combination with metham sodium and chloropicrin it gave similar performance to MB/PIC in California strawberry trials (Nelson *et al*. 2002).

4.4.3 Naturally occurring chemicals

Several natural fumigants (biofumigants) are directly active against target pests, while favouring or stimulating select groups of beneficial microbial species in soil (Canullo *et al.* 1992, Soler Serratosa *et al.* 1994). Some of the selected microorganisms are antagonistic to phytopathogenic nematodes and fungi (Canullo *et al.* 1992) e.g. root knot nematodes (*Meloidogyne* spp.), and fungi such as *Rhizoctonia solani* and *Sclerotium rolfsii*. The mode of action of these natural fumigants (selector compounds) involves short-term direct action against target pests and long-term activity through selection of beneficial microorganisms antagonistic to the pests.

4.4.3.1 Biorational pesticides

Biorational pesticides are formulations of microorganisms and/or plant extracts (Noling and Gilreath 1999). In the past few years, a number of biorational compounds (e.g. Fumafert, Dazitol, DiTera, Nemastop) have been evaluated for controlling nematodes and weeds (Anonymous 1998; Noling 2001). Most have provided inconsistent responses and none have provided control equivalent to that of MB. A combination of extracts of mustard meal and Neem, and mustard meal oil and an extract from chillies, have been shown to give broad spectrum control of nematodes and weeds (Seal 1997, Anon 1998, Chavarria-Carvajal *et al*. 1999b). In comparison to untreated soils, however, several have provided yield responses in the absence of any pest control and thus highlight the potential advantages of some of these products as a component of an IPM programme (Noling and Gilreath 1999).

4.4.4 Combinations of chemicals

Studies continue to demonstrate that some combinations of chemicals can provide a broad enough spectrum of control to be considered as effective MB replacements. These combinations may consist of two or more fumigants, two or more nonfumigant chemicals or fumigants and non-fumigant chemicals. Combinations can be developed to control a broad spectrum of pests equivalent or better than MB (e.g. Duniway *et al.* 1999, Frietas *et al.* 1999, Locascio *et al.* 1999, Porter *et al.* 1999, Nelson *et al*. 2002). However, overall efficacy of these systems may sometimes be limited by their ability to control key pests in a particular pest complex.

4.4.4.1 Fumigant mixtures

1,3-D/PIC. A large amount of research with 1,3D/PIC mixtures in several regions (Japan, US, Australia, Canada) has demonstrated that a broad range of pests and weeds can be controlled as effectively as MB (Gilreath *et al.* 1999b, Duniway *et al.* 1999, Locascio *et al.* 1999, Porter *et al.* 1999). Where registered, it is the main fumigant combination presently replacing MB. However, regulatory requirements limit the utility of this combination in some regions. Present regulations on 1,3-dichloropropene relating to area quotas, buffer zones and personal protective equipment are currently under review in USA and registrants are conducting research to reduce the impact of the regulations on use of this material

(Houtman 2000). In some crops, somewhat longer plantback periods than MB may be required.

Recent research has focused on application methods and new formulations to improve the efficacy of 1,3-D/PIC combinations (Lamberti *et al.* 2001a, Lópes-Robles and Martínes-Peña 1998, Soler 1997, Visbeck 1998). The development of a coulter plough application rig allows the use of 1,3-D/PIC formulations in sandy loam soils (e.g. Florida) (Chellemi *et al.* 2001). While effective for shallow rooted crops, shank application of 1,3-D/PIC formulations has not been demonstrated to be effective in fine textured soils where depth of control is critical. Research is planned on the use of emulsifiable formulations through drip application in these circumstances. In addition, emulsifiable formulations of 1,3-D/PIC, when applied by drip application, have shown promising results in research trials on strawberries and tomatoes in sandy soils (Locascio *et al.* 1999). This methodology has the potential to reduce offsite movement of fumigants and may also be more cost-effective than existing application methods (Trout and Ajwa 1999b).

In Canada, fumigation with a 1,3-dichloropropene/chloropicrin mixture (Telone® C-17) provided excellent control of weed seeds and weed species in soils of Nova Scotia strawberry nurseries (Jensen 2001).

In Japan, a mixture containing chloropicrin (40%) and 1,3-dichloropropene (52%) is registered. An improved application method utilizing this material has been reported to mitigate the odour problems associated with chloropicrin. Other mixtures of these compounds are under development (Tateya 2002).

Tomato yields in soils fumigated with 1,3-D with chloropicrin (17%) and the herbicide pebulate ranged from 81% to 117% of that obtained using MB fumigation in large-scale field demonstration/validation studies conducted on commercial tomato and pepper production farms in Florida (Case study 1). Uniform incorporation of pebulate was found to be a critical step to avoid early season phytotoxicity and a reduction in yield (Gilreath *et al.* 1997ab). While this combination with an effective herbicide works in tomatoes, lack of an effective, registered herbicide impairs adoption in some other similar crops.

1,3-D and MITC. Combinations of 1, 3-D and MITC are used in Europe, Canada and other countries (Thomson 1992). Combination treatments, such as with 1,3-dichloropropene and metham sodium, increased weed control an additional 5-10%, reducing the high cost of manual and mechanical weed control (Jensen 2001).

In the third year of a limited trial on sandy loam soil with 1,3-D as a drip applied soil treatment followed by a cap of metham sodium for replanting perennial crops in California, control continues to be comparable to MB (Schneider *et al.* 2001b).

MITC and PIC. Metham sodium and dazomet, alone or in conjunction with chloropicrin, are being used in countries where 1,3-dichloropropene has not been registered (e.g. see papers in MBAO 2000). Metham sodium in combination with chloropicrin and other materials (Enzone or Fosthiazate) give similar performance to MB/PIC in California strawberry research trials (Nelson *et al*. 2002)

MITC, 1,3-D and PIC. Combinations of chloropicrin with other products (e.g. 1,3-D, MITC), provides broad spectrum control of pests for which MB is used. (Ajwa *et al.* 2001, Lamberti 2001ab, Haar *et al.* 2001).

A product, Vorlex, containing a mixture of MITC, 1,3-D and chloropicrin has historically been registered in many countries and remains registered in at least 2 regions. It is effective against nematodes, fungi, weeds and soil insects (Thomson 1992). It is highly active even at low soil temperatures (4^{o}C). The product has been shown to be phytotoxic and long plant back periods may be required (Porter *et al.* 1999, 2002). The product was withdrawn from registration in the US in 1992, but is still registered in Canada and recently has outperformed methyl bromide for control of pathogens in trials on strawberries in Australia (Mattner *et al.* 2001). There has been renewed interest of this combination in research trials as an alternative to MB where it continues to have limited registration (e.g. Canada, Mexico).

Methyl iodide and PIC. Methyl iodide, in conjunction with chloropicrin, showed similar performance to a MB/chloropicrin mixture for disease control and production of a range of crops, including strawberries and tomatoes (Ohr *et al*. 1996ab, Becker *et al.* 1998, Allan and Schiller 2000, Hutchison *et al.* 2000, Nelson *et al*. 2002).

4.4.5 Chemical and non-fumigant chemical mixtures

A study conducted in a potato field indicated that reduction in nematode infected tubers of 23.7%, 8.7%, and 6.7% were obtained with metham sodium plus Temik, Telone II plus Temik, and Temik alone, respectively (Hafez and Sundararaj 2001). Metham sodium as part of an IPM system is used for control of Moko disease of bananas as an alternative to MB (Case study 3).

4.5 Non-chemical Alternatives

4.5.1 Resistant varieties and rootstocks

4.5.1.1 Varieties

Production of resistant cultivars involves incorporation of specific genes for resistance or tolerance and the selection of horticulturally acceptable plant types. The use of plant breeding to select and develop crop varieties resistant to or tolerant of pests is as old as agriculture. Development of resistant varieties, if genes are available, requires substantial research and development (Celada 1998, Tello 2002).

New varieties resistant to individual pests can be developed for some crops within 5 to 15 years depending on crop species and genetic resources. However, genes for resistance to some diseases have not been found. There are limitations to what can be done through plant breeding even with the recent advances in molecular techniques (Celada 1998). It is difficult to develop multi-resistant varieties as most fields are infested with a multiplicity of major and minor plant pathogens. The major limitations to the use of resistant varieties are the appearance of new races, high population levels of pathogens, and environmental conditions (Besri 1981, Besri *et al.* 1984, Besri 1993, Cap *et al*. 1993).

When feasible, use of varieties resistant or tolerant of soil-borne pests is a desirable component method in IPM systems because of their relatively low environmental impact (Rodríguez-Kábana 1998ab). There are resistant or tolerant varieties for most crop species today that lessen the requirement of MB. These include resistance to root-knot nematodes or pathogenic fungi, such as *Phytophthora, Fusarium, Verticillium,* and often bacteria (Garibaldi and Gullino 1990, Fery and Dukes 1996, Besri 1997ab, Cartia 1998, Browne *et al.* 2001)

4.5.1.2 Rootstocks

Grafting uses resistant rootstocks to protect susceptible annual and perennial crops against soil-borne pathogens. It is used with excellent results for controlling pathogens such as root-knot nematodes and fungal pathogens such as *Fusarium* spp., *Verticillium* spp. (vegetable and fruit crops) and *Phytophthora* spp. (peppers, fruit trees, citrus). Grafting can be as effective as resistant varieties (Miguel 1997, 1998, Nyczepir 2000, Anonymous 2001b, Bello *et al*. 2001, Lopez *et al.* 2002, Miguel 2002). Grafting of annual crops is widely used in some developing countries, e.g. Morocco (see Case study 4), Tunisia, Lebanon, Egypt, Jordan and Cyprus. Presently, 100% of the watermelon crop in Spain is raised from grafted plants, a practice that eliminated the use of MB on the crop in the Spanish south east (Tello 1998ab).

Rootstock resistance may break down with the emergence of new races of pests and pathogens, virulent populations and under some environmental conditions e.g. high temperature, salinity (Besri 1981, 1993). However, if a new race of the pathogen appears, it is easier to replace the rootstock than to develop a commercial resistant variety.

This technique, which formerly was considered too expensive is now in wide use in many developed and developing countries (Besri 1997ab, Gabarra and Besri 1997). Mechanical grafting techniques are available and widely used (Oda 1995, 2001b).

Grafted plants grown in solarised, biofumigated or chemically treated soils survive significantly better than the non grafted ones (Bello *et al*. 2001).

4.5.2 Physical Treatments: Heat

4.5.2.1 Solarisation

Soil solarisation occurs when heat from solar radiation is trapped under clear plastic sheeting to elevate the temperature of moist soil to a level lethal to soil-borne pests including pathogens, weeds, insects and mites (Katan 1993). Although it was first used in arid and semi-arid regions with intense sunshine and minimal rainfall, recent advances in technology have extended its use to other regions where it was once regarded as impractical (Horiuchi 1991, Chellemi *et al.* 1997ab, Le Bihan *et al.* 1997, Gullino and Minuto 1997, Lamberti *et al.* 2001b, Besri 2002, Ozturk *et al.* 2002). There are numerous studies on the use of soil solarisation for broad-spectrum control of pathogens and weeds, particularly in combination with fumigants, biocontrol agents and organic amendments. Even in hot climates, solarisation is more effective if combined with other methods. It can achieve control of pathogens to levels approaching those obtained with MB (Yücel. 1995, Gamliel *et al.* 2000, Minuto *et al*. 2000, Di Vito *et al*. 2000, Haidar *et al*. 1999, Haidar and Sidahmed 2000). Soil solarisation has been studied in over 50 countries including developed and developing countries (Katan 1991,1993, Ghini 1997, Tjamos 1998, Ammati *et al.* 2002ab, Besri 2002, Chaverri and Gadea 2002, Perez *et al.* 2002).

Results with solarisation are promising in many countries (e.g. Case studies 2,6,9,10,11) and inconsistent in others. There are some important pests e.g. root-knot nematodes (*Meloidogyne* spp.), nutsedge (*Cyperus* spp.), *Monosporascus cannonbellus* and *Macrophomina* spp., which are not consistently controlled by solarisation alone (Katan and DeVay 1991, Gilreath *et al.* 2001, López-Aranda *et al.* 2002). Results of demonstration projects carried out in Article 5(1) countries are presented in detail in Chapter 6. These results show that solarisation can be considered as alternative to MB, if the environmental conditions and cropping systems are favourable.

New technologies to improve the efficacy of solarisation and broaden its application are under development including sprayable mulches, double-layer plastic and virtually impermeable film (VIF). Painting the film with white latex paint after the solarisation period reduces the input costs (Tjamos and Niklis 1990, Gamliel and Stapleton 1993, Chellemi *et al.* 1997ab, Gamliel *et al.* 2001, Cebolla 2002ab). New plastic formulations that increase soil temperature have extended the usefulness of solarisation to cool regions (Fritsch *et al*. 2002, Stapleton 2000, Tamietti and Valentino 2000). The efficacy of solarisation can be improved when it is combined with fumigants or chemical pesticides, biological antagonists, organic amendments and appropriate cultural practices (Case study 6, Cartia and Asero 1994, Stevens *et al.* 1996, Cartia 1997,2002, Cartia *et al.* 1997, Lamberti 2001b, Llobell *et al.* 2000, Ammati *et al.* . 2002ab, Cebolla 2002ab. Lopez-Aranda *et al.* 2002).

Solarisation can also be used for disinfestation of containerised nursery soil (Stapleton and Ferguson 1996, Stapleton *et al*. 2001) and plant supports by storing these materials in empty plastic greenhouses during the off-season in hot climates (Besri 1991).

4.5.2.2 Steam

Steaming is the introduction of water vapour at approximately 100 ºC where it kills soilborne pests with the latent heat released when it condenses into water (Bungay 1999). During this process the soil temperature is increased to between 60-80 ºC for a specific period (4 to 8 hrs). Soil temperature and treatment duration determine whether complete elimination (sterilisation) or only partial removal of soil microflora (pasteurisation) occurs. When properly conducted, steaming is effective against all soilborne pests and a highly effective alternative to MB, having an equally wide spectrum of action and not requiring a waiting period before replanting (Gullino 2001, Miller 2001, Pizano 2001, Solis and Calderon 2002). Undesirable effects of soil sterilisation with steam at very high temperatures include pathogen recolonisation, release of heavy metals and phytotoxic materials. Thus soil pasteurisation is preferred (Runia 1983).

Steaming is a well-established and effective technique for soilborne pest control and is extensively used for bulk soil, soil treatments within greenhouses and some small-scale nursery plant operations (Nakano and Botton 1997). Steam can be applied by a number of methods of which sheet steaming and negative pressure steaming are the most favoured (Runia 2000). The latter technology improves energy efficiency by providing better dispersal of steam throughout the soil and reducing treatment time, particularly when treating clay or sandy soils (Runia 2000). It has been used successfully in demonstration projects in many developing countries e.g. Morocco (Ammati and Nyambo 2001, Ammati *et al.* 2002ab), Uganda, Zimbabwe and Uruguay (see Chapter 6) and is considered as an acceptable alternative to MB.

Steaming is most suited as an alternative to MB soil fumigation in protected cropping systems and for small scale, open-field production, e.g. bulbs and cut flowers and woody fruit and ornamental plants (Case study 20, Correnti and Triolo 1998, Rodríguez-Kábana 1998ab). Low pressure portable boilers makes small scale outdoor use of steam more feasible (Bungay 1999). Transportable machines for steaming in use in many countries for protected agriculture (e. g. Australia, Colombia) and are under development for broadacre use in several countries (e.g. Italy, Israel).

Steaming is slow and generally more expensive than treating with MB. It also has high demand for water, power or fuels (Crump 2001). Therefore, steam is more effective when it is a component of an IPM program (Pizano 2001).

4.5.2.3 Hot Water

Recent progress of an old technology hot water percolation has been developed as a physical alternative to MB in plastic houses in Japan (Kuniyasu and Takeuchi 1986). In this technology, field soil is slowly percolated with hot water at 70-95°C at a rate of 100 L m^{-2} through watering pipes or nozzles set on the soil surface. Recent trials have shown promising results on many soil borne pests (Eguchi *et al.* 2002, Iwamoto *et al.* 2000, Nishi 2000, Nishi *et al.* 2000, Nojima *et al.* 2002, Sakai *et al.* 1998). The technique controls *Monosporascus* root rot of melons which is not controlled by soil solarisation (Eguchi *et al.* 2002, Sakai *et al.* 1998).

4.5.2.4 Burning and flaming

Orobanche crenata and *O. aegyptica* (broomrapes) are very important parasitic higher plants on many crops, particularly on vegetables in the Mediterranean area. No resistant variety to these parasites is known. In protected cultivation MB is widely used to control these parasites. Preliminary experiments have found that burning the orobanche plants at the end of the growing season decreases the seed population in the soil and consequently the parasite incidence and severity (Besri 1998).

4.6 Crop Production Technologies

4.6.1 Organic amendments

Organic amendments such as composts, animal and green manures, by-products from agriculture, forest and food industries, are used in many countries to manage certain soilborne pests in various crops (Gamliel and Stapleton 1993, Ingham 1998, Cuester and Hoitink 1999ab, Lazarovitz *et al.* 2000, Lazarovitz *et al.* 2001ab).

Composted softwood and hardwood bark reduce the incidence of soil pathogens such as *Pythium ultimum*, a pathogen that causes damping-off under greenhouse and field conditions (Hoitink 1988). The addition of chitin into the soil suppresses *Rhizoctonia solani* and additionally may reduce nematodes and increase beneficial soil populations of actinomycetes (Rodríguez-Kábana 1998a). Compost has reduced MB use in a number of large commercial nurseries in California (Quarles and Grossman 1995). It was proved efficient in reducing populations of *Rhizoctonia* affecting ornamentals and horticultural crops in Argentina and for controlling *Fusarium* in carnation farms in Colombia (Pardo-Carrasco *et al.* 1998). Soil amendments with composted olive and fresh grape pomace caused a significant reduction of *Meloidogyne incognita* on melon in a sandy loam soil of southern Italy (D'Addabo *et al.* 2000).

Current limitations for the use of organic amendments include: lack of large scale manufacturers, inconsistency in product parameters due to lack of consistent quality standards, requirement for large amounts to be added to the soil, high transportation costs and regulatory constraints on use. Methods based on composting are by definition regionalized and efforts should be made to develop composts from inexpensive, locally available materials. This has occurred in some developing countries (e.g. Chaverri and

Gadea 2001). The degree of efficacy of composts against soil-borne pathogens will also vary regionally so that composts that control pathogens in one region may not do so in another region.

Organic amendments at this time cannot be considered as direct replacements for methyl bromide. However, evidence continues to accumulate that alterations in the populations of soil microorganisms induced by the addition of organic amendments can lead to long term decline in soil pathogen populations or in the development of disease suppressive soils. Thus, this approach is a valid long-term approach for reducing the need to use soil pesticides. As the understanding of the mechanisms by which organic amendments control pathogen populations increases and the effect of soil factors that are involved become more clear, the wide use of organic amendmemts will develop (Tenuta and Lazarovits 2002 ab, Conn and Lazarovits 2000).

4.6.2 Biofumigation

Biofumigation is a process where volatile toxic gases, released directly from roots or degrading organic amendments, control diseases, nematodes and weeds. Since the last report (MBTOC 1998), much research has been undertaken to improve biofumigation techniques and to develop a greater understanding of the mechanism of action of various byproducts released from organic amendments (Kirkegaard *et al.* 1993, Al-Rehiayani and Hafez 1999, Al-Rehiayani *et al.* 1999, Bello *et al.* 2001, Hafez and Sundararaj 1998, 1999ab, Bianco *et al.* 2001, Hafez and Sundararaj 2000ab, Cartia 2002, Lacasa *et al.* 2002a, Lopez *et al.* 2002, Lopez-Aranda *et al.* 2002).

The effectiveness of biofumigation may be improved by combination with plastic or other soil covers which heat soils and trap and enhance the effect of the volatiles. Incorporation of residues of some brassicas or Compositae has been shown to release a range of volatiles, particularly isothiocyanates, which have herbicidal, fungicidal, insecticidal and/or nematicidal properties (Bello 1998, Kirkegaard and Sarwar 1998, Gamliel and Stapleton 1993).

Biofumigation combined with solarisation considerably shortens the time necessary to accomplish pest control through solarisation alone (see Case study 2). The combination has been used successfully in the production of bananas, tomatoes, grapes, melons, peppers and other vegetables (Bello 1998, Sanz *et al.* 1998). In addition to disease control, organic matter stimulates soil microbial activity.

Incorporation of plants, *Tagetes* spp., into soil has been found to reduce nematode populations. However, *Tagetes* has no effect on fungal diseases and weeds. This technique is used in many countries on specific crops but due to its lack of broad-spectrum activity, it is not considered a direct alternative to MB (Bell *et al*. 1998).

Potential disadvantages of biofumigation have not been clearly defined, but they could include variable efficacy due to soil type, release of phytotoxic compounds, lack of available organic amendments, the delay of planting requirement to allow for amendment decomposition and their ability to become weeds if incorporated into soils after flowering.

4.6.3 Biological control agents

Biocontrol agents have been demonstrated to be effective for control of specific weeds, parasitic plants and soil-borne pathogens (Grondona *et al.* 2002, Verdejo-Lucas *et al*. 2002). Biological control of root pests uses non-pathogenic bacteria, fungi and other organisms that compete for space and nutrients or are antagonistic in some other manner toward pathogens in the rhizoplane, the rhizosphere or inside the root. In most cases they act as protectants against root infection.

Entomopathogenic nematodes have received considerable attention as control agent against insects and nematodes. (Lopez-Robles *et al.* 1997). The bacterium, *Pasteuria penetrans,* is effective for control of root-knot nematodes (*Meloidogyne* spp.) in cucumbers and other specific field situations (Stirling *et al.* 1995, Tzortsakakis and Gowen 1994). Pathogen-antagonistic *Fusarium* spp. proved effective against *F. oxysporum* f. sp. *dianthi* and *F. oxysporum* f. sp. *gladioli* and have been exploited commercially as biocontrol agents (Gullino 1995, Minuto *et al.* 1995, Postma and Rattink 1992). However, despite decades of research in the field of biological control, only a few microorganisms are on the market and are successfully applied in practice (Vannacci and Gullino 2000)

A specific substrate for plug trays containing two strains of endophytic fluorescent Pseudomonads is used in Japan for the control of bacterial wilt, Fusarium crown rot and root knot nematode of tomato (Aino *et al*. 2001). Tomato seedlings grown using this substrate also showed good resistance to similar pathogens when planted in soil.

IPM strategies using biological control as a component of a disease control program hold greater promise as a control tactic. They are most effective when combined with compatible chemical means of control at reduced dosage or genetic resistance where the plant's period of susceptibility is short and/or under cultural circumstances where heavy inoculation with microbial agents offers a distinct competitive advantage over pathogens (Winterbottom 1990, Winterbottom *et al.* 1996). Biological agents can be applied as seed dressings or other appropriate methods in combination with chemical treatments (Tjamos and Fravel 1997).

4.6.4 Crop rotations and cover crops

Crop rotation and cover crops have long been used as an important non chemical practice for soil borne pathogen management. A number of cover crops including castor (*Ricinus communis*), oat (*Avena sativa*), sorghum (*Sorghum bicolor),* crotalaria (*Crotalaria spectabilis*), sunn hemp *(C. juncea*), velvetbean (*Mucuna pruriens*), and various grasses, are known to be suppressive to root-knot nematodes. Although inferior to solarisation or soil fumigation, the performance of cover crops against nematodes may be improved by combining them with other methods, such as the use of nematode-resistant vegetable crops (McSorley 1998, 2000, Elberson *et al.* 1997).

In Costa Rica, promising results have been obtained on demonstration plots using velvetbean (*Mucuna* spp.) as a cover crop in melon crops. These amendments suppressed the root knot nematode (*Meloidogyne* spp.) and nutsedge weed (*Cyperus* spp.), but this alternative was not suitable for continuous cropping systems such as cut flowers (Chaverri and Gadea 2001).

Crop rotation and cover crops are more effective when considered in an IPM for the control of soil borne pests (Elberson *et al.* 1997, McSorley 2000).

4.6.5 Mulching

Translucent, photo-selective, infrared-transmitting mulch films significantly suppressed emergence of yellow and purple nutsedge (*Cyperus* spp.) in both greenhouse and field trials (Patterson 1997). Nutsedge is often the major remaining weed after soil treatments, including with MB. Grass mulches have been used to control *Sclerotinia sclerotiorum* (Ferraz *et al.* 1996).

4.6.6 Integrated Pest Management (IPM)

IPM is based on combinations of strategies and tactics to prevent or manage pest problems in an environmentally sound and cost-effective manner. Success of IPM has been reported from all over the world (Chellemi *et al.* 1996, Cartia 1998, Gullino and Clini 1998, Goncalves 1998, Gullino and Garibaldi 1998, Pizano 2001, Porcuna *et al.* 1997, Porter *et al.* 1997, Tio 1998). IPM systems are used in France as an alternative to MB for vegetable production in France (Case study 5). The development of suitable IPM strategies requires an intimate knowledge of the local agro-system. For this, site specific research should be conducted. In addition, the IPM implementation needs appropriate training for technicians and farmers

4.7 Alternatives that Avoid the Need for Soil Disinfestation with MB

4.7.1 Soilless culture

Soilless culture is a method in which plant growth substrates provide an anchoring medium that allows nutrients and water to be absorbed by plant roots. Requirements for the method include the substrate and systems for water and nutrient movement, decontamination and sanitation. The method can be applied at various levels of technological complexity. One of the purposes of using this system is to avoid, rather than control, soilborne pathogens, and thus obviate the need for MB. If recirculated nutrient solution is reused routinely, it requires disinfection to remove certain pathogens (e.g. *F. oxysporum* f. sp. *radicis lycopersici*, *Pythium* spp*., Phytophthora* spp., nematodes, bacteria) if they have accidentally become established.

Most of the soilless culture occurs in covered or protected agriculture (Barry 1998) (float tray systems for tobacco seedlings are a notable exception). Substrates include artificial and natural materials such as rock wool, tuff, clay granules, solid foams (e.g. polyurethane), glass wool, peat, coconut plant materials, volcanic gravel (lapilli) and pine bark (Aquino 1997, Diaz *et al.* 1998, Kipp *et al*. 2000). There are presently limited examples of open field operations but novel technologies being developed should expand this application in open fields (Rumpel and Kanizcwski 1998).

Soilless culture is used in developed and developing countries as a production method for crops such as: tomatoes, strawberries, cut flowers, melons, cucurbits, nursery-grown vegetable transplants and tobacco seedlings (Case studies 12,14,16,17,18,21, Besri 1997ab, Arbelo *et al.* 1998, Arias 1998, Reis 1998, Cartia 1998, Gullino and Garibaldi 1998, Tello 1998ab, Castellini 1999, Lopez *et al*. 2002, Lopez-Medina 2002, Marban-Mendoza 2002).

Constraints on soilless culture include availability of suitable substrates, ground water pollution from systems that do not recycle the nutrient solutions and the vulnerability of the system to pathogen attack.

The incorporation of beneficial fungi such as *Trichoderma* and bacteria into substrates has improved the use of soilless culture as an alternative to MB (e.g. Case study 15). Under appropriate conditions, the soilless method offers a better cost-benefit ratio than treating with MB (Canovas-Martinez 1997).

The use of soilless growing media has expanded in the last few years in both Article 5(1) and non-Article 5(1) countries. When an appropriate substrate is identified and is readily available, then large scale adoption often follows (e.g. rice hulls for cut flowers in Colombia, see Chapter 6). This technique offers a competitive system that avoids the need for MB to produce high quality and high yielding crops (Benoit 1992, Papadopoulos 1998, Kipp *et al.* 2000). Soilless production has predominantly gained acceptance for plant production in protected cropping situations or plant nurseries. Presently, the techniques are considered to have less potential to replace MB for large-scale open field operations because of limited availability of suitable local substrate materials. Nevertheless, the growth of this technology has been tremendous. For example, in China soilless culture increased from 1 ha in 1985 to 3150 ha by 2000 (Jiang *et al.* 2000). In 1999, about $4 billion dollars worth of horticultural crops were produced globally with soilless culture (http://www.ars.usda.gov.is.np.mba/apr99/perlite.htm).

The floatation tray method to produce tobacco seedlings is now used in many countries, such as Australia, Argentina, Brazil, Spain, Zimbabwe and Kenya at both large and small production levels. (Blanco 1997, Thomas 1999).

This method has replaced a substantial proportion (about 70%) of the MB formerly used globally in tobacco seedling production. The float bed is a simple hydroponic system that was developed by the tobacco industry for transplant production. It involves germination of seed in substrate such as vermiculite or peat mix in polystyrene plug-trays floating on a shallow bed of nutrient solution. Modifications of the float bed production system include the "Ebb and flood" procedure where periodic draining of the bed limits water availability and thus controls plant growth. This technique, as well as the floating tray method, have been shown to be highly effective for production of cabbage transplants. Overhead irrigation of the plant trays is now the most commonly used (Frantz *et al.* 1998).

4.8 Crop Specific Strategies

Despite the diversity of soil-borne pest problems world-wide, there are relatively few pests and diseases that are treated with MB. Historically the main limitation on MB use has been cost, restricting its use to certain high value crops. Table 4.1 summarises the major soil-borne pathogens (nematodes, fungi, bacteria, insects and weeds) for which MB is used in one or more regions of the world. Several fungal pathogens, root knot nematodes (*Meloidogyne* spp.), and some weeds, particularly nutgrass (*Cyperus* spp.) and broomrapes (*Orobanche* spp), are particularly problematic. The insect pests reported in the 1998 MBTOC report are no longer considered a major target for MB use, although they are controlled incidentally when MB is used.

Examples of alternatives to MB that have been implemented in non-Article 5(1) countries which have already phased out MB are provided in Table 4.2. Table 4.3 gives examples of alternatives being adopted for crops in non-Article 5(1) countries. Owing to the difficulty in obtaining reliable data, only certain countries have been updated since the 1998 MBTOC report. Table 4.4 details adoption of MB alternatives specifically in California, a major MB-using area. Several Article 5(1) countries have implemented a number of alternatives to MB for soil fumigation and these are shown in Table 4.5. A summary of the most important trends up until the end of 2001 are also included. MBTOC recognises that the uptake of some of the alternatives, especially non-chemical alternatives, are not known or reported and therefore it is difficult to obtain reliable data on their uptake. For this reason, only those alternatives that can be validated are indicated in Tables 4.3 and 4.5.

Nurseries: Pest control in nurseries is particularly important because the need to produce clean, 'disease free' plant material. This prevents the spread of pests to other regions and protects suppliers of nursery plants from litigation. Production of effectively pathogen-free planting material limits the need for treatments, such as with MB, in cropping areas. There has been a 30% reduction in the use of MB for nurseries in 2001 compared to the baseline and this corresponds to a shift to other chemical fumigants, including 1,3-D, chloropicrin and metham sodium, and to soilless systems.

Recent advances in substrate systems and production of containerised plants has made possible extensive growing of disease-free nursery stock without need for MB disinfestation treatments. There are now well-established procedures for growing of tree seedlings and many other nursery plants previously sometimes grown with the aid of MB. Initial capital cost is the main impediment to transfer from open field growing systems to substrate and containerised systems.

Ornamental crops: Owing to diversity of species grown, the high value of most ornamental crops, and associated risk of disease damage, especially those produced in protected environments, finding alternatives to MB for crops produced in soils is proving difficult. However, in several countries, a significant proportion of the ornamental crops previously produced in MB fumigated soils are now produced in substrate media, thus avoiding the need for soil disinfestation. Many of these crops still rely on soil disinfestation with MB or chemical alternatives if produced outdoors, and steam and fumigants if produced in protected environments. In protected environments, solarisation is adopted on a small scale where the climate and cropping systems allow. Steam is applied by fixed boilers, portable systems or by negative pressure systems.

Strawberry nurseries: Development of effective alternatives for production of strawberry nursery transplants in soil is limited by the high health requirement for strawberry runners and the need for excellent control of weeds. This has inhibited use of transitional strategies and many alternatives from being adopted as formulations of MB/PIC with low concentrations of MB are considered inadequate for weed control. Production of strawberry plants in substrates as plug plants, however, offers a technique which produces high health nursery plants that avoid the need for MB fumigation. There has been a significant increase in interest and application of this technology to suit production of runners worldwide, although further studies are required to determine the effects on strawberry physiology and fruiting and cost effectiveness for all production regions (Durner *et al*. 2002, Porter and Mattner 2002).

Perennial fruit and nut crops: In California, these cropping situations have been responsible for the largest decreases in use of methyl bromide since the baseline levels were imposed in 1995. The major chemical alternatives, 1,3-D and mixtures, has increased in usage to offset major decreases in the use of MB for almonds (76%), grapes (53%), plum/peach (53%), walnuts (68%), and sweet potatoes (42%) (Tables 4.3 and 4.4).

Strawberry fruit: In California, there has been no change in the use of methyl bromide for strawberry fruit production. In Australia, the major reduction in the use of MB has been achieved by adoption of transitional strategies where lower concentrations of MB in MB/PIC mixtures have been adopted. Recent registration of 1,3-D/PIC mixtures in this country is now proving an effective alternative. In Japan, however, chemical fumigation with 1,3-D and dazomet has offset a decline in MB use. A significant proportion of strawberries are produced without methyl bromide in many regions of the world. Substrate production of strawberries is practiced in cooler regions of the world, but has been considered uneconomic for warmer temperate zones.

Vegetables: Uptake of alternatives for vegetables has varied considerably depending on the crop and the region in the world where the crops are grown. In many regions of the world, many vegetable crops are grown successfully under IPM techniques (e.g. Canada, Argentina), mainly in substrates or sandy soils in protected environments without the need for methyl bromide (Papadopoulos 1998). In Spain, many of the vegetable crops previously produced with MB are now being grown successfully without fumigation (Bello, A, *pers. comm.*). Peppers are the only vegetable crop where a significant proportion of the crop is treated with MB. In Florida, however, growers are heavily reliant on MB fumigation because of the severe pest pressure from root knot nematodes and nutgrass. Recently, however, 1,3-D/PIC combined with selective herbicides has been as effective as MB over several seasons for these pests and a reasonable uptake (approx. 5% 1300ha) has occurred (Mirusso *et al*. 2002, D. Chellemi *pers. comm.*). In Australia, a major decrease in the use of MB has occurred for tomato crops because the cost of methyl bromide and limited availability has forced growers to utilise good crop rotations, IPM, metham sodium and selective use of herbicides. Alternatives for peppers are proving more difficult in Australia because of the difficulties in controlling *Phytophthora* (Anonymous 2001a).

Turf: In a number of non-Article 5(1) countries (e.g. USA, Australia) production of some turf (often certified) presents a small but very high value crop use for MB. Fumigation is used to ensure turf is true to type and kept weed and pathogen free. In particular, treatment of golf greens, fairways, racecourse and lawns for home gardens are prominent uses. Reduction in rate of MB in mixtures with chloropicrin are proving very effective in Australia for turf production on farms and dazomet is proving effective on small areas and where turf is laid within urban areas.

Other: In certain countries where the climate and cropping system allow, a significant proportion of MB use has been replaced for specific crop/pathogen complexes by an effective alternative (see Case Studies (Chapter 9), Chapter 6 and Tables 4.3, 4.5). For example, 10% of the melon production in Costa Rica uses solarisation instead of MB and Moko disease on bananas in Colombia is now controlled with dazomet and glyphosate.

4.9 Article 5(1) Perspective

Under Decision IX/5, Parties to the Montreal Protocol urged priority be given to resourcing projects by the Multilateral Fund that identified, evaluated, adapted and demonstrated MB alternatives in Article 5(1) countries. Detailed information on these alternatives can be found in Chapter 6. Demonstration projects did not aim to achieve actual MB reductions or phaseout. The demonstration project phase is now complete, and current MLF-funded projects aim to achieve partial or complete phaseout of MB in a country

As with non-Article 5(1) countries, the main techniques that give effective results comparable to MB in results are solarisation, steam, biofumigation, soilless culture and the chemicals, metham sodium, dazomet and 1,3-dichloropropene. Chloropicrin has also given good results, but is not easily available in some Article 5(1) countries. Combinations of alternatives generally have given the best results, particularly when they are part of an integrated pest management (IPM) program. Combined treatments (e.g. solarisation plus biofumigation or solarisation plus metham sodium) have given some of the best results.

Several successful alternative techniques to MB, proven to be effective in demonstration trials, have already been widely adopted for certain crop situations. For instance, floating trays utilising substrates have been widely adopted for tobacco seedling production in many countries for control of fungi (*Fusarium* spp.), nematodes *(Meloidogyne* spp.) and weeds *(Amaranthus retroflexus, Chenopodium album, Cuscuta* spp.) (Popsimonova 2001, UNIDO 2000, Calderón *et al.* 1999). In several countries, solarisation has been adopted on a wide scale (e.g. Costa Rica, Jordan, Lebanon) because treatment during the hot months of the year suits the crop management and crop rotation. Steaming has been adopted for several high value industries (e.g. floriculture) especially those where the high capital costs can be absorbed. Soilless cultivation is becoming a significant commercial trend in some intensively produced crops in many countries such as cut flowers, strawberries and vegetables. For example, about 25% of all flowers grown in Colombia are presently grown in substrates (Salazar 2001) and some rose growers in Kenya are converting production systems to soilless culture in pumice and cocopeat (Ammati and Nyambo 2001).

The main limitation to the adoption of new technologies in Article 5(1) countries has been the lack of accessibility to the technologies, lack of consistency against target pests, cost of implementation and regulatory restrictions which prevent access to some of the technologies. A further limitation is the lack of information and indicators to demonstrate which technology is best suited for control of a pest problem. Also, at this stage, the uptake of many technologies has been limited to growers or large multinational companies who have the necessary capital investment to access many of the new technologies. However, extension work carried out between research institutes, trade associations and growers are making wider adoption possible (Bernal *et al.* 2001, Castañeda *et al.* 2002, Pérez *et al.* 2002, Salles, 2001, Salles *et al.* 2001, Valerio, 2000).

Although the efficacy of alternatives has been facilitated by the large number of demonstration projects, further studies demonstrating long term commercial validation of alternatives are required before growers have the confidence on the usefulness of most alternatives.

Of the chemicals available, metham sodium has generally given good results in many different countries for many years, and is generally registered in Article 5(1) countries. It is also usually cheaper than other chemicals such as dazomet that is also effective (by 40% in Argentina, Salles *et al.* 2001). 1,3-D and mixtures with chloropicrin have given good control of a range of target pests and weeds, but registration constraints to this fumigant exist in some countries, particularly when formulations contain chloropicrin (Gullino 2001).

MBTOC noted that commercial trends to reduce the environmental impacts of agricultural production might increasingly affect Article 5(1) producers of export crops. Several commercial programs and agricultural standards now aim to restrict MB fumigation as part of a package of measures to reduce the use of pesticides and other practices that can harm the environment. For example, the 'MPS' environmental grade system for cut flowers has been adopted on about 5,000 farms in 22 countries (e.g. Costa Rica, Ecuador, France, Italy, Israel, Kenya, Netherlands, USA, Zambia and Zimbabwe). Growers who enter the programme are generally not permitted to use MB as a soil fumigant.

4.10 Areas yet to Find Alternatives to MB for Soil Treatments

Research studies have not yet identified conclusively that MB can be replaced in certain production systems, especially those where 'high health' and certification requirements exist.

This includes perennial tree and other replant situations where target pests may be deep in the soil and the production of pest-free propagation material to meet legislative requirements. Since 1998, research has shown some promising alternatives for perennial replant uses, but further research is required before commercial adoption is widespread. These include the improved application of 1,3-D/chloropicrin by use of micro-irrigation, the use of soil-applied streptomycin and activated charcoals and the manipulation of rhizosphere bacteria (McKenry 1999, Brown 1999, Mazzola 1999, Trout and Ajwa 1999b, Schneider *et al.* 2001b).

In several places worldwide, there is still a mandatory and increasing requirement for the treatment of soils with MB to satisfy certification requirements, such as turf in parts of the United States.

Also several pests of certain crops are proving difficult to control - root rot of ginseng replant in China and CGMMV and pepper mild mottle virus (PMMoV=TMV-pepper strain) in Japan. Previous studies evaluating a range of fumigant alternatives (chloropicrin, carbam, metham sodium and dazomet) found none of the alternatives was effective at the low temperatures required at the beginning of the melon cropping season. However, they did confirm the effectiveness of MB (Inoye *et al.* 1967, Nagai 1981, Nagai *et al.* 1974, Takeuchi 2000). In addition, soil solarisation failed to control these tobamoviruses (Nagai 1981, Takeuchi 2000). Although CGMMV has not been a serious problem in Japan since the 1960-1970s, recent outbreaks on 2.8 ha of cucumber fields required fumigation with MB for control.

Table 4.1 Major soil-borne pathogens (nematodes, weeds and parasitic plants) for which MB is used in one or more countries in various regions of the world in 2001.

Target pests	North America	Central & South America	Northern Europe	Mediterranean Region	Sub-Saharan Africa	Asia	Australasia
Nematodes							
Meloidogyne spp.	+	+	+	+	+	+	+
Rotylenchulus spp.	+	+	-	-	-	+	-
Xiphinema spp.	+	+	-	-	-	-	-
Belonolaimus sp.	+	-	-	-	-	-	-
Fungi							
Armillaria spp/Rosellinia spp.	+	-	-	-	+	-	+
Fusarium spp.	+	+	+	+	+	+	+
Phytophthora spp.	+	+	+	+	+	+	+
Pythium spp.	+	+	+	+	+	+	+
Rhizoctonia spp.	+	+	+	+	+	+	+
Sclerotinia spp.	+	+	+	+	+	-	-
Sclerotium rolfsii	+	+	+	+	+	+	+
Verticillium spp.	+	+	+	+	+	+	+
Bacteria							
Agrobacterium tumefaciens	-	-	-	-	+	-	-
Clavibacter michiganensis	+	-	-	+	-	-	-
Pseudomonas spp.	-	+	-	-	-	-	-
Ralstonia solanacearum	-	+	-	-	-	+	-
Weeds and Parasitic Plants							
Orobanche spp.	-	+	+	+	+	-	+(QPS)
Cyperus spp.	+	+	-	+	+	-	+
Replant Problems							
(Perennial Crops)	+	+	+	-	+	-	+

1 May be important in one or more countries in the region
+ Methyl bromide or alternative considered necessary for this pest.
- Methyl bromide not considered necessary or pest not present

Note 1: Those pests are listed that, if all other pests were excluded, would still be target pests for MB or alternatives
Note 2: Pests affecting specific uses (e.g. crop specific certification) have not been considered in the table. In the United States a range of nematodes are controlled with MB to assist certification of nursery stock and turf. Also an additional 20 different pests, pathogens and weeds are still considered major targets for MB use in parts of the USA (e.g.. Florida and California).
Note 3: This table does not imply that the pests currently targeted with MB cannot be controlled by other means.

Data Sources:

Survey data collected by MBTOC from Agricultural Ministries and Departments of Environment.
Californian Department of Pesticide Regulation.
Florida Agricultural Statistics Service (1995). Vegetable Chemical Use.
USDA (1994) Agricultural Chemical Usage. USDA National Agricultural Statistics Service, Economic Research Service, Washington DC.
Australian National Methyl Bromide Response Strategy (1998). Environment Australia.
MBTOC Assessment (1995).
The Netherlands Policy Note, Lower House (1980

Table 4.2 Non-Article 5(1) countries that have phased out methyl bromide

Country	Crop	Proportion of Crop Treated with MB the Year before Phaseout	Quantity of MB Used (t) the Year before Phaseout [1]	Main MB Formulation Used prior to Restriction	Estimated Proportion of Alternative Cropping Practice Adopted to Replace MB Use since Phaseout
Holland [1]	Tomatoes	65%	1,200	MB (100) used in 1980	90% substrates 10% steam
	Cucurbits	30%	300	*ditto*	90% substrates 10% steam
	Cut Flowers	25%	800	*ditto*	60% substrates 30% steam 10% metham sodium with 1,3-D
	Flower bulbs (glasshouse)	90%	300	*ditto*	70% metham sodium with 1,3-D 25% crop rotation and flooding 5% steam
	Strawberries	75%	200	*ditto*	90% substrates 10% metham sodium
	Total all crops		**3,000**		
Denmark [2]	Tomatoes, lettuce, cut flowers	NA	26	MB/PIC 98:2	99% substrates 1% steam
	Total all crops		**26**		

[1] MB use shown for the year 1980 which represents levels in Holland before restrictions were imposed, total phaseout 1991.
[2] Total phaseout on 1 January 1998.

Table 4.3 Examples of alternatives to soil fumigation with methyl bromide used in major crops in non-Article 5(1) countries

Country	Crop	Proportion of Crop Treated with MB		Quantity of MB Used (t)		Main MB or MB/PIC Formulation Used Prior to:		Estimated Proportion of Alternative Practice Adopted Commercially since 1994 to Replace MB Use as of:	
		1994	2001	1994	2001	1994	2001	Jan 1997	Jan 2001
Australia	Tomatoes (fresh) Pepper	50%	35%	290	130	98:2	98:2	Nil	6% metham 23% IPM (i.e. 30% use fresh land; 20% fumigate less often,10% nematicides)
	Flowers / Bulbs	15%	10%	140	65	98:2	50:50	70% MB/PIC 70:30 and 20% IPM + MB	70% MB/PIC 50:50 and 20% IPM 5% metham 5% dazomet 2% Telone C35
	Strawberry fruit	65%	65%	130	55	70:30	50:50 or 70:30	10% MB/PIC 50:50	30% MB/PIC 70:30 35% MB/PIC 50:50 7% MB/PIC 30:70 10% metham
	Strawberry Nursery	98%	98%	30	28	70:30	70:30	Nil	Nil

Australia (cont.)	Protected crops (Flowers, vegetables)	5%	5%	70	50	98:2 or 100%	98:2 or 100%	5% steam	5% substrates
	Orchard replants	2%	2%	7	5	98:2	70:30	70% MB/PIC 70:30	70% MB/PIC 70:30
	Turf	10%	10%	8	15	98:2	50:50	Nil	5% dazomet
	Total all crops			**679**	**350**				
Japan	Melons	NA		741		MB/PIC 98.5:1.5	MB/PIC 98.5:1.5	15% PIC, 1,3-D or dazomet alone	15% 1,3D/PIC 20% dazomet 13% unknown
	Cucumber	NA		526		98.5:1.5	98.5:1.5	15% PIC, 1,3-D or dazomet alone	15% 1,3D/PIC 20% dazomet 13% unknown
	Watermelons	NA		963		98.5:1.5	98.5:1.5	15% PIC, 1,3-D or dazomet	15% 1,3D/PIC 20% dazomet 13% unknown
	Ginger	NA		557		98.5:1.5	98.5:1.5	5% PIC	20% dazomet
	Ornamentals	NA		225		98.5:1.5	98.5:1.5	15% PIC, 1,3-D or dazomet	15% 1,3D/PIC 20% dazomet; 13% unknown
	Pepper	NA		273		98.5:1.5	98.5:1.5	12.5% PIC, 1,3-D or dazomet	15% 1,3D/PIC 20% dazomet 13% unknown
	Tomato	NA		323		98.5:1.5	98.5:1.5	12.5% PIC, 1,3-D or dazomet	15% 1,3D/PIC 20% dazomet 13% unknown
	Strawberry fruit	NA		326		98.5:1.5	98.5:1.5	15% PIC, 1,3-D or dazomet	15% 1,3D/PIC 20% dazomet 13% unknown

Japan (cont.)	Seedbeds	NA		359		98.5:1.5	98.5:1.5	15% PIC or steaming	NA
	Total all crops			**5,648**					
Spain	Cucurbits	0.4%		175		98:2	98:2	MB rate reduction	MB rate reduction
	Pepper	9.2%		1,186		98:2	98:2	<40g/m^2 and PE or 20g/m^2 with VIF films (legislatory requirement)	<40g/m^2 and PE or 20g/m^2 with VIF films (legislatory requirement)
	Tomatoes	0.4%		149		98:2	98:2		
	Vegetables (general)	0.4%		730		98:2	98:2	Use of other fumigant and non fumigant alternatives increased	Use of other fumigant and non fumigant alternatives increased
	Ornamentals	30%		470		98:2	98:2		
	Strawberry fruit	39%		972		67:33	67:33		
	Strawberry nursery	100%		432		67:33	67:33		
	Citrus (replant)	0.1%		78		98:2	98:2		
	Tobacco (seedbeds)	0.5%		46		98:2	98:2	100% substrates	100% substrates
	Total all crops			**4,238**		**98:2 (85%) 67:33 (15%)**	**98:2 (85%) 67:33 (15%)**	**25% reduction (legislatory requirement)**	

USA 1.California	Almond	NA	NA	332	102	MB/PIC 98:2		NA	
	Walnut	NA	NA	249	79	98:2		NA	
	Grapes	NA	NA	956	446	98:2		NA	
	Nurseries	NA	NA	1054	711	NA		<1%	
	Strawberry nurseries	100%	NA	174	1917	57:43 67:33		<1%	
	Strawberry fruit	98%	NA	1,969		50:50 to 98:2		<1%	
	Orchard (plum/peach)	NA	NA	287	135	98:2		NA	
	Sweet potato	40%	NA	282	163	98:2		<7%	
	Tomatoes, Peppers (Fresh)	2%	NA	312	277	67:33 85:15		<2%	
	Total all crops			**>6742**	**3882**[1]				**For all crops, see Table 4.4**
USA 2. Florida	Cucumber	100%	NA	113	NA	98:2	NA	<1%	<1%
	Eggplant	100%	NA	75	NA	98:2	NA	<1%	NA
	Melons	70%	NA	67	NA	98:2	NA	<1%	NA
	Peppers	100%	NA	1,569	NA	98:2 (80%) 67:33 (20%)	NA	<1%	5% adoption of 1,3 D/PIC combined with herbicides

2.Florida (cont.)	Tomatoes	100%	NA	3,732	NA	98:2 (60%) 67:33 (40%)	NA	<1%	5% adoption of 1,3 D/PIC combined with herbicides
	Strawberries	100%	NA	501	NA	98:2 (80%) 67:33 (20%)	NA	<1%	NA
	Total all crops			**Approx 6,000**					

[1] Total of crops listed in table; actual use for all crops is greater. Usage numbers based on data from Cal. Dept. of Pesticide Regulation and T. Trout (pers comm.)

Table 4.4 Comparison of the changes in the quantity of chemical fumigant use in California from the 1994 to 2001

Country	Crop	Quantity of MB Used (t)		Quantity of 1,3-D Used (t)		Quantity of Chloropicrin Used (t)		Quantity of Metham Used (t)	
		1994	2001	1994	2001	1994	2001	1994	2001
USA	Almond	332	102	48	112	<1	3	0	4
1.California	Walnut	249	79	7	28	Nil	11	2	1
	Grapes	956	446	24	289	4	5	19	25
	Nurseries	1054	711	4	70	109	177	50	95
	Strawberry nurseries	174	1917	NA	NA	NA	NA	NA	NA
	Strawberry fruit	1,969		0	6	864	1081	18	30
	Orchard (plum/peach)	287	135	2	112	<1	6	1	3
	Sweet potato	282	163	34	230	1	<1	85	46
	Tomatoes, Peppers (fresh)	312	277	47	33	27	111	296	252
	Total all crops	**>6742**	**3882** [1]	**166**	**880**	**1005**	**1396**	**471**	**452**

[1] Total of crops listed in table; actual use for all crops is greater. Use numbers based on data from Cal. Dept. of Pesticide Regulation

Table 4.5 Some Article 5(1) countries which have implemented alternative practices to soil fumigation with methyl bromide

Country	Crop	Proportion of Crop Treated with MB		Quantity of MB Used (t)		Main MB or MB/PIC Formulation Used Prior to:		Estimated Proportion of Alternative Practice Adopted Commercially since 1994 to Replace MB Use as of:	
		1994	2001	1994	2001	1994	2001	Jan 1997	Jan 2001
Argentina	Tomato, pepper, eggplant (seedbeds, protected)	100%	NA	7	NA	98:2	NA	20% substrates	NA
	Tobacco (seedbeds)	100%		171		98:2	NA	15% cultural, chemical	
	Ornamentals	5%		12		98:2	NA	99% cultural / chemical	
	Strawberry	None		None		NA	NA	100% MB/PIC 80:20 introduced	
	Total all crops			**244**				**348t MB used in 1997**	
Colombia	Bananas	70%	0%	45	Nil	98:2	Nil	93% dazomet + glyphosate with IPM	100% dazomet + glyphosate with IPM
	Total all crops			**72**	**10**				

Costa Rica	Melon	100%	90%	500	450	98:2	98:2	Sector increased MB use but trials with alternatives started (cover crops, solarisation, metham sodium, 1,3-D, dazomet)	10% of melon area (500 ha) uses solarisation. Other alternatives like metham sodium, 1,3-D are implemented on commercial areas.
	Total all crops			**600**				**689t MB used in 1998**	
Morocco	Tomato, cucurbits, strawberry, beans, pepper, bananas, ornamentals	68%		1,025		98:2		Limited adoption. Increased exports have led to existing and new growers increasing their use of MB, however some farmers use alternatives and have never used MB	Limited adoption. Increased exports have led to existing and new growers increasing their use of MB, however some farmers use alternatives and have never used MB
	Total all crops			**1,025**				**c. 1,085 in 1997**	

Uruguay	Tomato, pepper	NA		10 (increasing to 21t in 1997)	41 [1]	MB/PIC 98:2	MB/PIC 98:2	NIL. Sector increased MB use. With the aid of demo project alternatives were identified and awareness increased	20% solarisation + metham sodium or biofumigation (tomato growers). Some using VIF films. MB reduced by 80% in 2002
	Total all crops			**11.9**				**22t in 1997 and 42t in 2000**	

Data sources for Tables 4.3, 4.4 and 4.5

Survey data collected by MBTOC from Agricultural Ministries and Departments of Environment.
Californian Department of Pesticide Regulation.
Florida Agricultural Statistics Service (1995). Vegetable Chemical Use.
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MBTOC Assessment (1995).
The Netherlands Policy Note, Lower House (1980)
UNIDO project on alternatives to MB for banana production in Colombia
Colombian ozone office
UNIDO project on alternatives to MB for the horticultural sector
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Ozone Office of Uruguay
Ozone office Costa Rica
Regional workshop on MB for Latin America and the Caribbean, Bogotá, Colombia, 1995

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Chapter

5

Alternatives for treatment of durables, wood products and structures

5.1 Introduction

This chapter summarizes control of pests in durables, wood products, packaging materials, structures, and transport.

Durables are commodities with a low moisture content that, in the absence of pest attack, can be safely stored for long periods. They include artefacts, i.e. bamboo ware, museum and cultural artefacts; beverage crops, such as cocoa and coffee; cereal grains, e.g. wheat, rye, barley, rice, sorghum, maize; dried fish, dried meat and derived meals; dried fruit and nuts; grain products, including flour, noodles, semolina; herbs and spices; pulses, such as peas, beans and lentils; tobacco (post-harvest); wood products and packaging materials.

A few commodities are held at intermediate moisture contents (water activities), but tend to be treated as durables. Examples are fresh chestnuts and some fresh dates. These commodities may be subject to moulding and spoilage unless held under special conditions. These intermediate moisture content commodities are considered in this chapter. Perishable commodities are considered in the chapter (Chapter 7) on Quarantine and Pre-shipment (QPS), since their treatment with methyl bromide almost is likely to fall under the QPS exemption.

Most durable commodities currently treated with methyl bromide are foodstuffs that are stored post-harvest sometimes for long periods, before being consumed, processed or traded in or out of a country between harvests. Pest control in durables is performed to reduce insect populations to below a detectable level in order to prevent damage to the commodity and protect consumers. Many pests can survive and proliferate on durables in storage and infestations can spread further down the supply chain.

Generally, wood products requiring treatment with methyl bromide can be classified into two categories, those items separate from buildings and structures and those forming an integral part of a structure.

Structural pest control is used to prevent or control pests in either an entire structure or a portion of a structure. Many conditions and pests exist which require structural pest control; only some of these are treated by methyl bromide fumigation. There are two main applications: 1) control of direct structural damage by drywood termites and wood-boring beetles found in domestic, commercial and historic buildings, 2) control of pests, for example moths, beetles, cockroaches, mites, nematodes and rodents, in storage, food processing and non-food facilities, and in transport vehicles.

Structural fumigation for facilities with food pests is a pest management technique that provides broad-spectrum control. The fumigant gas penetrates to reach pests that are not on the surface and cannot be readily contacted by other types of pesticide applications. This ability to penetrate through packaging materials, walls, and other areas to hidden infestations is particularly valuable for structural treatments. Treatments of premises against food pests can involve empty buildings or those containing goods.

Treatment regimes for transport are often subject to stringent time constraints. Times out of service for aircraft and ships can incur severe consequences for operators. Thus alternatives for methyl bromide fumigation need to provide a means for a rapid solution to problems.

It is estimated that approximately 15% of the annual world non-feedstock usage of methyl bromide is for the disinfestation of durable commodities and about 2.5% for structures.

There are a large number, and variety, of potential or existing alternatives to methyl bromide for disinfestation of durable commodities and structures. The choice of an alternative is dependent on the commodity or structure to be treated, the situation in which the treatment is required, the accepted level of efficacy and the cost. Some alternatives (e.g. some fumigants, heat treatment) may be implemented as stand alone treatments to replace methyl bromide in certain situations. In general, however, the level of control achieved may only become acceptable by combining two or more alternatives.

5.1.1 Target pests

Most of the target pests of durables, wood products, and structures that are treated with methyl bromide are insects and, to a lesser extent, mites. Fungi and nematodes are not typically target organisms, except with unsawn timber and seeds for planting, respectively. The principal target insect pests for the various durable commodities sometimes treated with MB are given in Annex 5.1.

5.1.2 Types of fumigation enclosure

For safety and efficient action, it is necessary to enclose the commodity to be treated with some form of system, the fumigation enclosure, which restricts loss of gas to a low level.

The most efficient method of fumigating bagged or cased commodities is in chambers equipped for applying the fumigant in a manner that will ensure its rapid and even distribution, typically, a recirculation system of some type (Bond 1984). Fumigation of commodities is also carried out:

- under gas-proof sheets of various thicknesses
- in warehouses
- in specially sealed transportable plastic enclosures ('bubbles')
- in freight containers
- in silos
- in railway box-cars
- in barges and ships
- in specially designed and equipped vacuum chambers

5.2 Existing Uses of Methyl Bromide

Of the estimated 9855t of methyl bromide used on durables and wood products in 1992 (1994 MBTOC estimates), it was estimated 472t (5%) was used on dried fruit and nuts, 4782t on timber and the remainder (4601t, 47%) used mainly on cereal grain and legumes with minor uses on other commodities. A recent survey showed consumption of 4,218t for cereal grain, legumes, dried fruit and nuts and similar materials, and 4,107t on timber in 2000, showing a 15% decrease in quantities used since 1992.

Many of the uses of MB on durables fall within the Quarantine and Pre-shipment (QPS) exemption under Article 2H. These are discussed in Chapter 7.

5.2.1 Uses for durables

Methyl bromide has been in widespread use as a fumigant for foodstuffs and other stored products for more than fifty years. Methyl bromide remains the major pest management process for several high value commodities in trade, such as dried fruit, nuts and cocoa beans. There are also numerous low volume uses, such as disinfestation of particular kinds of dried herbs and spices, particular specialized cereal grains and products, and certain dried animal products and meals. Commercial interest in registering chemical alternatives is hampered by market size, developmental and registration costs to permit their use. Methyl bromide often is the only registered chemical that can be used. The susceptibility of various pests of durables to MB is given in Annex 5.2 and dosage schedules in Annex 5.3.

In general, methyl bromide currently plays a significant role in the overall treatment and protection of wood products and timber. Most of these treatments are for QPS purposes, discussed in Chapter 7.

Methyl bromide is registered for a wide variety of structural treatments, both for treatment of wood-destroying pests and food pests. It is effective against all life stages of insects and vertebrates. It penetrates well and permits short fumigation times, a very important issue for food processing facilities and transport. Methyl bromide can be used on an entire structure or a portion of a structure. Treatment duration is dependent upon the time taken to achieve a set *ct*-product. Ideally sufficient gas to kill the pests is released into the space and then maintained at the toxic level for a defined period of time. The current practice in many countries is to fumigate with methyl bromide during a three-day weekend when operations are typically suspended for preparation of the structure, a 24 h treatment exposure, and up to 24 h airing period.

5.2.2 Uses for which MBTOC did not identify alternatives

There are some current non-QPS uses of methyl bromide for which MBTOC did not identify any existing alternatives.

For durables these are: disinfestation of fresh chestnuts, disinfestation of fresh walnuts and dates for immediate sale, elimination of seed-borne nematodes from alfalfa and some other seeds for planting, and control of organophosphate-resistant mites in traditional cheese stores. In treatment of mills and food processing facilities where IPM systems have not proved adequate, it may be necessary to resort to occasional use of methyl bromide. Except in those few countries where hydrogen cyanide is available for insect control in aircraft, there are no proven alternatives to methyl bromide. In addition there is no recognised alternative for control of wood-destroying fungi *Serpula lacrimans* in historical structures. The total requirement of methyl bromide for these uses is unlikely to exceed 150 tonnes per annum.

5.3 Durable Products

Generally, the commodities classified as durables normally have less than 15% moisture content. They include:

- Artefacts, including bamboo ware, museum and cultural artefacts
- Cereal and legume seeds and grains, e.g. wheat, rye, barley, rice, sorghum, maize, pulses, including peas, beans and lentils, and cereal products, including flour, noodles, semolina and pasta
- Dried fruit and nuts, beverage crops, including cocoa and coffee
- Fishmeal, dried fish, meat and derived meals, cheese
- Herbs and spices
- Seeds, for planting (considered under QPS, Chapter 7)
- Tobacco (post-harvest), and other non-food vegetable crops such as cotton (see Chapter 7)
- Unsawn timber and timber products (considered under Wood Products, Section 5.4, and Chapter 7)

5.3.1 Artefacts

The preservation and protection of artefacts represents a broad area of interest including commercial interests (e.g. trade in artefacts) and artefacts of substantial value or of irreplaceable cultural and national significance. Many of the objects held in museums, libraries and similar repositories are subject to attack by rodent and insect pests and, at high humidity, by fungi. Damage can be extensive if pests become established (i.e. begin to reproduce, eat, excrete, and die) in the museum collection. Infestable materials include those made of wood, paper, leather and skins, feathers, natural fibres (particularly wool). Pest insects hidden deeply in the material can be effectively and quickly treated with fumigants having high penetrability. Duration of treatment however is not generally important. Therefore alternatives requiring extended periods of treatment are acceptable provided that they are effective and produce no adverse effects on the artefacts or risks to health or the environment.

Since artefacts may be severely damaged by attack from a single insect, museums, libraries and similar repositories try to avoid infestation and damage to their valuable and unique objects. Consequently, many museums, libraries and similar repositories have installed a precautionary system to ensure that only insect-free artefacts enter the location. Emphasis is thereafter focused on reducing the chances for survival of damaging pests.

None of the pests occurring in museums are specific to artefacts. They originate from other sources. In museums the requirements for a treatment are that it is effective against the target pest and at the same time causes no damage to the artefact itself, or, in case of space fumigations, to the surrounding materials. Data on composition and history of the material may be limited or unknown and experience about the effect of the treatment on the included materials may be limited or absent. Artefacts often include a variety of different materials (e.g. wood with ornaments, herbaria, different combinations of natural fibres, feathers and fur, leather and skins), which must be considered prior to the choice of treatment.

5.3.2 Grains and similar commodities

A wide variety of stored cereal grains, and grain legumes (pulses), have been treated with methyl bromide. Examples for cereals and legumes, including flour, pastas, semolina and compounded animal feed, are given in Table 5.1. This category also includes similar products such as sago and cassava chips. Cereals provide the staple diet in most countries. They are stored in various ways starting from small scale on farm or domestic storage facilities to larger scale bag storage, often fumigated as a sheeted bag stack, to storage in bulk in grain silos or sheds. The quantities of grain and similar commodities

Table 5.1 Examples of cereal and legume crops that may be fumigated with methyl bromide

Common name	**Scientific name**
Barley	*Hordeum vulgare*
Beans	*Phaseolus* spp., *Vigna* spp.

Buckwheat	*Fagopyrum sagittatum*
Cassava	*Manihot esculenta*
Lentil	*Lens culinaris*
Maize	*Zea mais*
Millet	*Pennisetum* spp.
Oats	*Avena sativa*
Peanut	*Arachis hypogea*
Peas	*Pisum sativum*
Pigeon pea	*Cajanus* spp.
Rice	*Oryza sativa*
Rye	*Secale cerale*
Sorghum	*Sorghum bicolor*
Soybean	*Glycine max*
Wheat	*Triticum aestivum*

stored therefore range from a few kilograms to many thousands of tonnes at one site. In general, smaller scale shorter-term storages are of primary importance in Article 5(1) countries (see Chapter 6) whereas larger scale longer-term storage is of primary concern in non-Article 5(1) countries. Many treatments are carried out under QPS requirements, particularly those related to pre-shipment prior to export or transport between trading nations. Common pests encountered on cereals and related products are found in Annex 5.1.

5.3.3 Dried fruit, nuts, coffee and cocoa

The commodities described in this section possess diverse physical and chemical characteristics. They may be stored for extended periods of time, both before and after processing. Many of these commodities, particularly coffee and cocoa, are typically produced in developing countries and shipped to developed countries that demand a high standard of quality and total absence of infestation by pests. In many production areas storages are of inadequate quality to protect the commodities from invasion by pests and the ambient high temperatures and humidities may favour their rapid multiplication. Infestations can lead to severe economic losses unless effective control measures are applied. Losses result not only from direct damage and downgrading as a result of pest activity, but also from charges levied by importing countries where fumigations are carried out at point of import, should infestations be detected. Internal infestations of commodities such as walnuts, apricots and cocoa may also emerge during storage at the final destination.

Dried fruit and nuts have particular quality characteristics, which must be taken into account when considering application of technologies developed for pest control. In particular, some dried vine fruits are susceptible to sugaring when held at low temperatures, and sultanas may change colour (increased brownness) and lose grade when subject to high temperatures for extended periods. Walnuts, cocoa beans and some other products are susceptible to taint when treated with some chemicals.

Commodities covered in this section, at least sometimes treated with methyl bromide, are given in Table 5.2 below. Most of these products are harvested over a relatively short period and at the same time. Often very large volumes have to be treated quickly to eliminate infestation brought in from the field and prevent in-store damage or prepare the goods for trade or export. As an extreme example, receiving stations in the U.S. can handle 26,000 tons per day of dried fruits and nuts at the peak of the season. Currently, most dried fruits and nuts are treated at least once with methyl bromide. Rapid disinfestation for both domestic and foreign markets needs to be considered when evaluating alternatives.

The stored product moth and beetle pests must be treated in order to avoid damage to the product as well as sometimes to meet market or regulatory standards. Reinfestation by storage pests may occur in local and importing country storage, during transit and subsequently in marketing channels and consumer storage.

Table 5.2 Varieties of fruits and nuts sometimes treated with methyl bromide

Common name	**Scientific name**
Nuts and beans	
Almond	*Prunus amygdalus*
Beechnut	*Fagus* spp.
Betel nut	*Areca catechu*
Brazil nut	*Bertholletia excelsa*
Butternut	*Juglans cinera*
Cashew	*Anacardium occidentale*
Chestnut	*Castanea* spp.

Cocoa beans	*Theobroma* spp.
Coconut	*Cocos nucifera*
Coffee beans	*Coffea arabica*
Cola-nut	*Cola acuminata*
Hazelnut (filbert)	*Corylus* spp.
Hickory nut	*Carya* spp.
Macadamia nut	*Macadamia tenuifolia*
Pecan	*Carya illinoensis*
Pinenuts	*Pinus* spp.
Pistachio	*Pistacia vera*
Walnuts	*Juglans* spp.
Dried fruit	
Apple	*Malus* spp.
Apricot	*Prunus armeniaca*
Banana	*Musa* spp.
Blueberry	*Vaccinium* spp.
Cherries	*Prunus cerasus*
Cranberry	*Vaccinium macrocarpon*
Date	*Phoenix dactylifera*
Fig	*Ficus carica*
Mango	*Mangifera indica*
Papaya	*Carica papaya*
Peach, nectarine	*Prunus persica*
Pear	*Pyrus* spp.
Pineapple	*Ananas comosus*
Prune	*Prunus domestica*
Raspberry	*Rubus idaeus*

Sultanas, currants and raisins	*Vitis* spp.
Tomato	*Lycopersicon esculentum*

5.3.4 Animal products

Commodities damaged by pests include both saltwater and freshwater dried (cured) fish, dried meat and meat products, bone meal and fish meal. The alternatives that may be technically effective for these minor-volume products may be limited by registration and other regulatory constraints.

The common pests of animal products are mostly dermestid beetles. Dried fish and fish meal is particularly prone to infestation by several species of dermestids and to a lesser extent by the clerid beetles *Necrobia* spp. Damage caused by dermestids can be particularly severe, and it has been reported from inland fisheries in Africa, that if infestation is not controlled, losses approaching 50% of the commodity can result (FAO 1981). Dried meat may also become infested by similar insect pests, but no information is readily available on economic losses caused to this product.

Currently no process known to MBTOC has been able to address the problem of replacing methyl bromide to control pesticide-resistant mites in traditional cheese stores.

5.3.5 Herbs and spices

The fruits, leaves, seeds and other parts of many dried plants are used for medical purposes or as seasonings, beverages and food additives are subject to in infestation by stored product pests (Table 5.3).

These high value products are usually grown in tropical regions. They may become infested prior to harvest, or in store in the country of production. Typically these commodities are either bagged or baled and fumigation is usually conducted under gas proof sheets in warehouses, in specialist fumigation chambers, or in shipping containers.

Many spices and herbs are produced under conditions where there may be excessive bacterial contamination for particular markets, and as well as measures for pest control, sterilisation procedures have to be employed. In the past, many herbs and spices were sterilised by ethylene oxide fumigation, but this is now no longer permitted in many countries.

Table 5.3 Herbs and spices sometimes disinfested with methyl bromide

Common name	Scientific name
Basil	*Ocimum basilium*
Bay	*Laurus nobilis*

Chillies	*Capsicum* spp.
Cinnamon	*Cinnamonum zeylanicum*
Cloves	*Syzygium aromaticum*
Coriander	*Coriandrum sativum*
Fenugreek	*Trigonella foenum-graecum*
Ginger	*Zingiber officianale*
Marjoram	*Origanum marjorana*
Mint	*Mentha* spp.
Mustardseed	*Brassica juncae*
Nutmeg/mace	*Myristica fragrans*
Oregano	*Origanum vulgare*
Parsley	*Petroselinum crispum*
Pimento	*Pimenta dioica*
Rosemary	*Rosemarinus officianalis*
Saffron	*Crocus sativus*
Sage	*Salvia officianalis*
Sesame	*Sesamum indicum*
Tarragon	*Artemesia dracunculus*
Tea	*Camellia sinensis*
Thyme	*Thymus vulgaris*
Turmeric	*Curcuma domestica*
Vanilla	*Vanilla fragrans*

5.3.6 Tobacco

Tobacco is a high value commodity transported internationally either raw or as finished products (cigars, cigarettes). Pest species of importance are *Ephestia elutella* (warehouse or tobacco moth) and *Lasioderma serricorne* (cigarette beetle)

5.4 Wood products, structures and transport

5.4.1 Protection of wood and wood products

For pests that attack wood, alternatives can be classified into two types of treatments, whole-structure or localized. Whole structure treatment is defined as the simultaneous treatment of all wooden members, whereas localized treatment is restricted to a group of boards or locations within boards (Scheffrahn and Su 1994). For localized treatments accuracy in detection of and determining the extent of infestation is critical to optimising pest control service and providing effective treatment. Alternatives that can provide whole-structure treatments include fumigation with sulphuryl fluoride or other fumigants, and various heat applications.

Generally, wood products, which require treatment with methyl bromide, include:

- Artefacts, museum objects, and other items of historical significance
- Unsawn timber, timber products, furniture and other wood products
- Bamboo ware, packaging materials and other items of quarantine significance

For recent reviews on alternative treatments for wood products, timber and artefacts see Banks (2002) and Reichmuth (2002).

Table 5.4 describes typical uses in structures.

Table 5.4 Types of buildings and structures fumigated against wood pests

Structure fumigated	Associated pests
Dwellings including apartments, condominiums, trailer homes, historical buildings, commercial premises	Drywood termites, furniture beetles, powder post beetles, long horned beetles
Museums	Wood boring beetles, dermestid beetles, clothes moths, cigarette beetles, drugstore beetles
Structural elements before building or in place, e.g., beams	Powder post beetles, long horned beetles
Antique vehicles	Powder post beetles

5.4.2 Control of food pests in structures and transport

The necessity to minimise pest infestations and attempt to eradicate pests in products is well documented. Pests that infest durable commodities and food products often become established in the fabric of the buildings or structures where food is stored or transported. Infestations can migrate throughout the building from such sites, or be transported to new premises and infest other products. Therefore, structural treatments can involve empty buildings or transport vehicles, or those containing goods. This underscores the need for maintaining pest infestations at the lowest practical level. The choice of treatment depends on the goal. The level of control required varies between both countries and industries. Pest elimination may require full site treatment, which today usually includes use of a fumigant, while satisfactory pest control may be achieved in many cases by other treatments. New techniques being developed have the potential to achieve elimination without the use of fumigation.

Table 5.5 describes the situations in which methyl bromide may be used as a space fumigant to disinfest premises and transport together with the classes of pests concerned.

5.4.2.1 Ships

Methyl bromide is currently the only fumigant allowed for many quarantine treatments on ships in many countries, but is no longer recommended for in-transit fumigation in ship holds or for fumigation even where ventilation is carried out prior to sailing (IMO 1996) However this practice is reported to continue to be in use in many parts of the world. Cargo may be treated in the vessel with methyl bromide at the discharge port, with ventilation carried out prior to discharge. Methyl bromide is also used, usually as a last resort, for the disinfestation or deratting of empty ships.

Table 5.5 Uses and targets for structural fumigation to control urban and food pests

Description	Examples of Pests
Food Production and Storage Facilities	
Food processing plants Flour and feed mills Bulk commodity storage (e.g. silos) Warehouse Bakeries Ham smoke houses Cheese plants Refrigerated storage Restaurants	Stored product insects, rodents, cockroaches, psocids, mites, silverfish, beetles
Non-food Facilities	
Seed warehouses Museums Poultry houses Mushroom houses Condemned housing or public health compliance	Rodents, stored product insects Dermestid/anobiid beetles, clothes moths Lesser meal worm, mites, rodents Mushroom flies, mites Rodents, cockroaches, venomous spiders

Transport Vehicles	
Trucks, truck trailers, vans (empty)	Beetles and moths
Ships, shipholds, gallery and quarters (empty)	Insects and rodents
Railcars (freight or commodity)	Insects and rodents
Buses	Insects
Aircraft	Cockroaches, other insects, rodents, reptiles

5.4.2.2 Aircraft

Currently, methyl bromide continues to be used to fumigate aircraft, usually for rodent control, but occasionally against insects. This practice is limited to a few locations worldwide. For insect control, residual or aerosol insecticide applications are usually used. Methyl bromide provides a rapid and guaranteed kill which is essential in the context of the cost of grounding aircraft and the risks to the aircraft if the rodents are not killed. Carbon dioxide is reported to have been introduced in the Netherlands to control rodents, and hydrogen cyanide is used in several countries for this purpose.

5.4.2.3 Freight containers

Fumigation of freight containers can be carried out either before (pre-shipment) or after transport (post shipment). Methyl bromide is not allowed for intransit fumigation under the current International Maritime Organisation recommendations (IMO 1996). All containers under fumigation are classified as Dangerous Goods under the International Maritime Organisation Dangerous Goods Code, the provisions of which allow phosphine fumigation in transit, which may replace some pre and post shipment fumigations with methyl bromide.

5.4.2.4 Other vehicles

Vehicles such as catering trucks or railway coaches are sometimes fumigated with MB for general pest control purposes. The use of MB for this purpose in California is diminishing due to local regulations. Commercial vehicles and railway cars may require treatment to meet quarantine legislation when empty and prior to loading. In some countries MB treatment is currently mandatory.

5.5 Alternatives for Durables and Structures

Alternatives in present or past use, or in the process of investigation or development are described here. Many alternatives are measures designed to preclude the need for methyl bromide use, rather than direct replacements for existing uses. As with methyl bromide, use of alternatives may have human health and environmental consequences, which must be taken into consideration. Regulatory actions within each country may affect the availability or applicability of an alternative chemical, such as, for example, the absence of a particular commodity or use on the registration label or the prescribing of substantial exclusion zones around fumigation enclosures. Many of these potential alternatives have not been tested on large volumes of commodities requiring rapid turn around, particularly for QPS purposes. The regulatory burden for some will be substantial if the new use is to be confined to particular durable commodities or type of structure.

Aside from cost, the choice of an alternative is dependent upon the commodity to be treated, the situation in which the treatment is to be done, and the level of risk. Risk can be determined in relation to treatment failure, degradation of commodity value, and human or environmental well being.

5.5.1 Biological methods

Biological agents are generally host specific and considered to be primarily preventive control measures. They are not directly comparable with methyl bromide fumigation because of their specificity, except in instances where only a few species of target pests are prevalent. Biological methods have potential to provide long-term protection for stored commodities in specific situations. (Plarre *et al*. 1999, Faroni *et al*. 2000, Schoeller 2000, Prozell and Schoeller 2000, Ekesi *et al*. 2001, Flinn and Hagstrum 2001, Dorn *et al*. 2002, Lucas and Riudavets 2002).

Arthropod parasitoids and predators are naturally-occurring in stored commodities, but rarely suppress a storage pest before unacceptable damage occurs. Therefore, mass-release or augmentative approaches will be needed to overwhelm pests before they can do harm (Flinn *et al*. 1996). Some of the more effective parasitoids are *Bracon hebetor*, which attacks larvae of moths (Brower and Press 1990, Cline and Press 1990, Schoeller 2000), *Trichogramma* spp. that attack eggs (Brower 1988a,b, Stengaard-Hansen 2000), *Lariophagus distinguendus*, which attacks larvae of *Sitophilus* species (Steidle and Schoeller 2000), and *Choetospila elegans* which attacks *Rhyzopertha dominica* and other species (Flinn 1998). The primary target pest species are flour moth and Indian meal moth larvae or eggs and various beetle larvae. *Bracon hebetor* has commercial use in South Africa for reducing the need for fumigation of stacks of bagged grain and dried vine fruit (Anon. 1991) and is used to control Indian meal moth in stored peanuts in the South-Eastern U.S. Baker and Throne (1995) utilized an insecticide-resistant parasitoid with chemical treatment for control of weevils in wheat. Recent studies have indicated that the pteromalid, *Lariophagus distinguendis,* has potential for control of *Sitophilus granarius, Rhyzopertha dominica* and *Callosobruchus maculatus* (Steidle *et al*. 2002, Reppchen *et al.* 2002). Also the number of insect fragments in flour could be significantly reduced by prior release of parasitoid wasps in stored wheat (Flinn and Hagstrum 2001).

The effectiveness of the predatory warehouse pirate bug, *Xylocoris flavipes*, has been evaluated in regulating stored product pest populations (Press *et al*. 1975, Brower 1988ab, Brower and Mullen 1990, Brower and Press 1992). After introduction of large numbers of the pirate bugs in storage premises, the populations of *Tribolium castaneum* can be suppressed in a short period of time (Press *et al*. 1975, Wen and Brower 1994). The histerid beetle *Teretriosoma nigrescens* (Lewis) has been used successfully to suppress populations of the serious maize pest *Prostephanus truncatus* in the laboratory and in the field (Rees *et al*. 1990, Giles *et al*. 1996). The predatory mite *Acarophenax lacunatus* has been shown to be effective in suppressing populations of *R. dominica* (Faroni *et al*. 2000).

Pathogens of insects include bacteria, viruses, protozoa, nematodes, and fungi. Among these, the bacteria, viruses and protozoa have been most studied for use as control agents for stored product insects. Commercial formulations of *Bacillus thuringiensis* (Bt) provide control of almond moth and Indian meal moth when applied to grain as an aqueous suspension or as a dust. These are effective when all the grain is treated, or when just several inches of the surface layer are treated, because lepidopterous larvae usually live near the surface of the bulk. Potentially, Bt and other pathogens can form part of an IPM strategy, although some resistance has already been detected in stored grain moths (McGaughey and Beeman 1988). Bt is exempt from a tolerance in the U.S.A., but not in other countries, for use as a stored product protectant. Residual activity against susceptible insects can last for more than a year (McGaughey 1986). Vail *et al.* (1991, 1996) and Dandekar *et al.* (1998) report the screening and development of several lines of transgenic walnut with high levels of the insecticidal Bt crystal protein fragment that arrest development or kill larvae of codling moth, navel orangeworm, and Indian meal moth, the principal targets for methyl bromide fumigation of stored walnuts.

Some entomopathogenic fungi were described as possible control agents but efficacy was poor (Dal Bello *et al*. 2001, Ekesi *et al*. 2001). Entomopathogenic viruses (primarily baculoviruses) have been studied for the control of post harvest pests of grain, dried fruit and nuts (Hunter *et al*. 1973, McGaughey 1982, 1986, Cowan *et al*. 1986, Kellen and Hoffmann 1987, Vail *et al*. 1991, 1993ab). The granulosis virus of Indian meal moth is now registered as a protectant for dried fruits and nuts by the US EPA (Vail 2002).

5.5.2 Botanicals

These compounds are derived from plants. Botanicals seem more likely to form part of an IPM system or be used for small on-farm use in Article 5(1) countries, and as such may not be direct replacements for methyl bromide. Botanicals may more correctly be considered to play a role in preventing fumigation. At present, the only botanical in widespread use in developed countries for protection of durables is pyrethrum extract. Pyrethrum has toxic and repellent properties (Ndalut and Saggar 1996). Others, such as azadirachtin, an active principle from neem, are registered in some countries for plant protection and under continuing investigation for durables. Botanicals may have limited application in developed countries because of concerns about transferring odours or off-flavours to milled or processed products. A wide variety of botanicals are still used by subsistence farmers on staple crops in developing countries.

There is continued research on development of numerous botanicals for control of stored product pest insects and even mites (Shaaya *et al*. 1997, Pemonge *et al*. 1997, Huang *et al*. 1997, Keita *et al.* 2000, Tapondjou *et al.* 2000, Adler *et al.* 2000, Obeng-Ofori *et al.* 2001, Bouda *et al*. 2001). As natural products are not readily patented, there is little incentive for companies, and other organisations, to pay for the toxicological testing required to gain registration for use, particularly in non-Article

5(1) countries. This is a constraint for their successful introduction for specific uses on durables as methyl bromide alternatives, possibly except when data is already available to support registration as a food additive.

5.5.3 Carbon bisulphide

Application to large bulk storage is restricted by the potential fire hazard of the material and safe methods for large-scale use have not been developed. In most countries its use has been discontinued and registration has lapsed. There is some use in China where it is typically used for small lots of grain (c. 50 tonnes) in farm storage. Investigations on carbon disulphide in Australia by Desmarchelier (2000) have shown that there are many factors involved in deciding on the best strategic options for using this chemical. One strategy favoured by the author is that use be restricted to situations where fumigant residues would not be a problem..

5.5.4 Carbon dioxide at high pressure

For many years, controlled atmospheres at atmospheric pressure have been used to replace methyl bromide for disinfesting some dried fruit and beverage crops. A recent innovation combines carbon dioxide with high pressure of around 20 bar. This controls all stages and species of pest insects in less than three hours. It requires a gastight chamber, which can withstand pressure of this magnitude. Carbon dioxide under high pressure is in limited use in Germany to treat beverages, nuts and spices (Prozell and Reichmuth 2001, Prozell *et al*. 1997). The high construction and operating costs of pressure chambers restrict their widespread use. The process has also been investigated in France and Japan (Le Torc'h and Fleurat-Lessard 1991, Nakakita and Kawashima 1994, Nakakita *et al.* 2001) and more recently in Spain (Riudavets *et al.* 2002). The rate at which the pressure can be released affects the efficacy of action (Nakakita and Kawashima 1994, Ulrichs 1994), but in practice there are physical constraints on the rate at which pressures can be manipulated.

5.5.5 Carbonyl sulphide

Carbonyl sulphide is a promising fumigant, with high penetration and mobility rate under consideration for registration for durables, including timber and wood products, in Australia. Banks *et al.* (1993a) patented the gas as an insecticide. Carbonyl sulphide did not adversely affect the quality of malting barley, or wheat (Desmarchelier 1994). Sorption of carbonyl sulphide by wheat is very low. Wheat contains natural levels of the gas. Carbonyl sulphide does not appear to affect the seed viability of wheat (van S. Graver 1994). Effective control of a variety of insect pests was obtained in investigations with barley and canola by Ren *et al*. (2000) using carbonyl sulphide. Reuss and Annis (2000) fumigated paddy rice and rice products with carbonyl sulphide at 20 g m^{-3} and found that residues were below the MRL levels proposed, and that the viability of paddy was not adversely affected. It appears to be an effective fumigant for disinfesting non-perishable commodities such as timber (Viljoen and Ren 2001) and has been shown to be toxic to termites. The fumigant has shown activity against durable commodity pests, including *Sitophilus granarius, S. oryzae, Rhyzopertha dominica, Oryzaephilus surinamensis, Carpophilus hemipterus,* *Lasioderma serricorne and Tribolium confusum* (Plarre and Reichmuth, 1996, Zettler *et al*. 1997, Weller and Morton 2001).

5.5.6 Cold treatments

Cooling typically is used to prevent damage of products and multiplication and reinvasion of pest. The technique is used for disinfestation in specific instances, such as for museum objects or small quantities of seed or products where a mild non-chemical disinfestation is required. Under these circumstances, they can present an alternative to methyl bromide use. Cold treatments are now used as part of integrated pest management systems for stored products (including grains, cereals, oilseeds and seeds) and for structures where freezeouts are used as space treatments in warehouses or grain storages (Fields and Muir 1995, Banks and Fields 1995, Rulon *et al*. 1999). The technique is more commonly used in countries with low ambient temperature after harvest, for example in Canada (Worden 1987), but is also used where cold storage warehouses are part of a storage system (for example for prunes in USA and France).

Fields (1992) and Banks and Fields (1995) reviewed the effect of cold on insect and mite pests. Below about 10°C insect reproduction ceases and infestation of populations of most pests of durables slowly decline. At 4°C adults of most species survive for many months, though immatures may be killed. Species of tropical origin, such as *Sitophilus oryzae*, *S. zeamais, Tenebroides mauritanicus* and *Lasioderma serricorne* tend to be cold sensitive, although some important pests including *Cryptolestes* spp., bruchids, mites and some Lepidoptera are very tolerant (Armitage 1987, Lasseran and Fleurat-Lessard 1991, Fields 1992, Fields and White 1997). In consequence, cooling to about 2°C typically requires very long holding times (several weeks) to be effective. Insects may adapt to cold, prolonging their ability to survive (Fields and White 1997, Burks and Hagstrum 1999).

Most pests require only a few hours or days exposure at very low temperatures (-15^{o}C or below) to ensure control (Chauvin and Vannier 1991, Fields, 1992). The stage of development of the pest is a factor in its cold resistance: eggs are more sensitive, and adults and larvae are often the most cold tolerant (Banks and Fields 1995). Indian meal moth, *Plodia interpunctella,* and tobacco moth, *E. elutella*, diapausing larvae are highly cold tolerant, requiring over 14 days and over 4 weeks respectively at -10^{o}C (Bell *et al.* 1991), while adult rusty grain beetles, *Cryptolestes ferrugineus,* require two weeks at a grain temperature of -15^{o}C, six weeks at a grain temperature of -10^{o}C, or eight weeks at grain temperature of -5^{o}C, for control (Banks and Fields 1995). In addition, some species of insects have the ability to acclimatise to cold and may become tolerant to otherwise lethal cold temperatures (Fields *et al*. 1998). For this reason, rapid cooling after harvest is required to prevent cold acclimatisation and improve insect control.

5.5.6.1 Use on bulk grain

On a large scale, cold treatments can involve aeration by ambient cold air applied under the grain bulk or into the grain bin or by the transfer of grain from one bin to another in cold weather, leaving it outside if possible for a few days before returning it to storage (Marcotte 1995). Aeration plays a most important role in preventive control measures at a cost sometimes competitive with curative disinfestation processes such as fumigation with methyl bromide (Armitage *et al.* 1991).

5.5.6.2 Other applications for the use of cold in stored product pest control

Cold treatments can be used with care to disinfest artefacts, provided condensation and cracking of wood and other sensitive materials can be avoided by appropriate control of moisture. Blast freezers providing treatment at -40°C for 24 hours have been used to disinfest book collections (Smith 1984). Exposure to -18°C can control all common stored product pests in foods as well as clothes moths in woolen artefacts (Brokerhof *et al.* 1993).

Cooling to very low temperatures (-10 to -18°C) is an established system of disinfestation of dates, replacing methyl bromide treatment. It is most effective when combined with a brief exposure to low pressure or 2.8% oxygen, which causes insects to leave the centre of the fruit (Donahaye *et al.* 1992), making them vulnerable to the cold treatment. A 10.5 hour exposure to -10°C, or 2.25 hour exposure to -18°C, killed all stages of the relevant insect pests (Donahaye *et al.* 1991).

Cold storage has not been widely practiced for storage of dried vine fruit because of concerns about the crystallisation of sugars. It is used for some dried fruits, for example prunes, dried pears, and organically produced vine fruits and is appropriate for nuts and beverage crops. Organic raisins are held for up to a year at -0.5 to 1°C, 90% r.h., in polythene-lined bins after drying to 11% m.c.

The cowpea weevil (*Callosobruchus maculatus*) was found to be easily controlled by the temperatures found in commercial freezers. With rapid cooling rates, insect numbers were reduced by more than 99% in exposures of 6-24 hours. (Johnson and Valero, 2000). Cooling, combined with nitrogen CA treatment in sealed, white-painted silo bins is in use in Australia for protection and disinfestation of in-shell almonds (Banks, H.J. pers. comm.).

Extreme cold has also been used in the tobacco industry (Ryan 1995). All stages of cigarette beetle *Lasioderma serricorne* can survive up to 3 hours at -15°C (Meyer 1980). Diapausing larvae of the warehouse or tobacco moth required 4 weeks at -10°C for control (Bell 1991). For cold treatment, exposure of cases for 5 days in a commercial draught-assisted freezer (-30 °C) is recommended (Ryan 1995).

The utility of very low temperatures as disinfestants needs to be checked for other products.

5.5.6.3 Cold treatments for structures

Cold treatments are used as part of integrated pest management systems and for disinfestation of structures (Fields 1992, Fields and Muir 1995, Banks and Fields 1995). The technique is more commonly used in countries with low ambient winter temperatures (for example, Canada) but is also used where cold storage warehouses are part of a storage system (for example for some dried fruit in the US and France).

Freezeouts have been used as space treatments to kill pests in mills, warehouses or storages. This method is also used for seed warehouses. Water pipes, when present in the building, must first be drained and temperature sensitive equipment must be moved. As an alternative to whole site exposure, cold air directed to localized infested areas within a facility can provide local protection against infestation.

5.5.7 Construction and removal

New construction should be designed for pest exclusion and prevention as a priority so pests cannot gain access to a building and the structure does not provide inaccessible harbourage for pests. For example, in many situations constructing wooden structures in a manner which protects the wood from humidity, destroying the conditions necessary for pest development can be substituted for the use of chemical wood preservatives and protect the wood against attacks.

Infested wood in dwellings can often be cut out and replaced. While this can be an effective spot treatment, it is labour intensive. Where permitted, infested wood should be replaced with pre-treated wood.

5.5.8 Contact insecticides

Unlike fumigants, contact insecticides, including dichlorvos, may provide persistent protection against reinfestation. These chemicals can be applied as dusts or sprays either directly to grain, wood, wood products and artefacts for protection against insect pests, or to storage buildings and transport vehicles as part of a sanitation programme to reduce the likelihood of cross-infestation or re-infestation of commodities. They are not normally registered for use on processed commodities. Grain protectants, typically organophosphate and pyrethroid insecticides, do not readily penetrate bagged or bulk grain. This restricts their utility substantially as normally they must be applied to the grain during handling, e.g. prior to bagging or on to grain on conveyors or elevators.

The use of grain protectants varies widely with country, market preference and local regulations. Where permitted, and where pest resistance is not a problem, they can provide a useful means of avoiding the circumstances resulting in the need for fumigation. Besides their applications on grain, contact insecticides have been used as aqueous dips for other purposes. They have been used on seeds to control seed borne nematodes, on protecting dried fish from insect attack, and on museum artefacts.

Generally, fumigants, such as methyl bromide, have a somewhat different action on pests and role in stored product protection to contact insecticides. Despite these differences, where permitted by market preference and regulatory authorities, both techniques can result in pest-free end product.

5.5.8.1 Contact insecticides in stored grain and other commodities

Organophosphorus compounds are an important group of grain protectants in current use. The stability of deposits on grain varies widely with particular material and ambient conditions. The rate of degradation increases both with temperature and water activity (moisture content). Furthermore, toxicity to insects tends to increase with temperature. In consequence, persistence of the biological effectiveness will depend upon the insecticide used. For example, typically dichlorvos acts quickly and degrades within a few days, while malathion takes several weeks, and pirimiphos methyl many months.

Dichlorvos is unique amongst grain protectants in its rapid action against pests and lability on grain. In the absence of resistance, and where approved, it can be sprayed onto bulk grain during conveying. Subject to an adequate withholding period for the residues to decay to acceptable levels, such a treatment can provide a direct alternative to disinfestation with methyl bromide. While dichlorvos is currently approved under the Codex Alimentarius Commission (1992) for application to raw cereal grains with a maximum residue level of 2 g t^{-1}, the registration continues to be subject to debate in some countries and its long-term future use is not assured. The limited suitability of dichlorvos, either in combination with controlled atmospheres (Ding *et al*. 2002), or other contact insecticides against psocids has recently been described (Nayak *et al*. 2002). In the U.S.A., the food additive tolerance for dichlorvos is under review, thus in the future it may not be permitted where processed or packaged food will be contacted. This effectively limits its use and its toxicity may lead to further restriction and unavailability.

Most organophosphates are poorly effective against bostrichids (*Rhyzopertha dominica* and *Prostephanus truncatus*). The principal materials used worldwide include: chlorpyrifos methyl, dichlorvos, fenitrothion, malathion, and pirimiphos methyl, but other organophosphates may be registered and used in specific countries. Pirimiphos methyl has been recommended as an aqueous dip for dried fish (Golob *et al*. 1987). A maximum residue limit of 10 mg kg^{-1} was recommended for pirimiphos methyl by the FAO/WHO Committee on Pesticide Residues (FAO, 1986). Currently there are concerns regarding the development of resistance to organophosphates and the occurrence of residues on bulk grain itself and in finished products. Registrations vary between different countries, so there are potential problems with import/export regulations. In addition, regulatory issues such as the 1996 Food Quality Protection Act in the US and similar legislation in European Union and elsewhere have and will affect continued registration of some organophosphates used in grain protection.

Synthetic pyrethroids are a group of insecticides with chemical constitution based on that of the active ingredients of natural pyrethrum. In contrast to organophosphates, residues are quite stable on grain and their insecticidal activities may persist up to 2 years (Snelson 1987). Toxicity of pyrethroids may decrease with increases in temperature. Pyrethrins synergised with piperonyl butoxide have been recommended as an aqueous dip for protecting dried fish from insect infestation (Proctor 1972). Pyrethroids are generally active against bostrichid beetles at a much lower dosage than for most other insect pests of durables. A disadvantage of these pesticides is their relatively high cost. In many situations pyrethroids are added in combination with a synergist, piperonyl butoxide, to increase effectiveness and reduce cost. Pyrethroids used in different countries as grain protectants include: resmethrin, bioresmethrin, deltamethrin, pifenthrine and cyfluthrin.

Dalglish and Wallbank (2000) have indicated the continuing need for contact insecticides and that the development of resistance to those in current use requires that new alternatives are necessary. The principal reason for using contact insecticides is to meet the need for insect free grain, and in particular to control the lesser grain borer *R.. dominica*.

5.5.8.2 Contact insecticides in museums, wood and wood products

Contact insecticides are used as part of pest management strategies in museums and repositories. A variety of specific insecticides is used, depending on national regulation/approval, but contact insecticides based on pyrethroids (e.g. permethrin, cypermethrin, deltamethrin, cyhalothrin) or on organophosphates (e.g. dichlorvos, chlorpyrifos) seem to be the most common.

In Japan, artefacts such as museum specimens, collections, library, antiques and art crafts are treated with the pyrethroids cyphenothrin (applied as a 1% solution in liquid carbon dioxide) to control cigarette beetle, powder post beetle (*Lyctus brunneus*), black carpet beetle, book borer anobiid (*Gastrallus immarginatus*), oriental silverfish (*Ctenolepisma villosa*) and others, and phenothrin (applied as a 1% solution in liquid carbon dioxide) to control cockroaches, fleas, bedbug and *Ornithonyssos* spp. (fowl and rat mites).

For wood in structures, surface application/injection of liquid residuals is used for spot application to accessible wood. The products used for this application include organophosphates (e.g., chlorpyrifos), pyrethroids (e.g., permethrin), and borates (e.g., sodium octaborate tetrahydrate). These products are applied as sprays, fogs, brush-ons and/or injections for treating accessible components. The efficacy of organophosphates and the pyrethroids against wood destroying insects is well documented. For some wood-destroying pests sodium octaborate tetrahydrate has proven effective, when adequate penetration of the wood can be achieved. Tests undertaken on the efficacy of borates for drywood termites have shown limited efficacy (Scheffrahn *et al*. 1997).

Wood Preservative Treatment is a method of preventing wood destroying insect problems by applying a pesticide or preservative to wood pre-construction. Some materials used for wood impregnation have been discontinued because of environmental effects. Pentachlorophenol was broadly used at one time, but is only in use in a few countries now. A wide range of preservatives is available for vacuum or pressure treating wood, for example borates and copper- containing compounds. Preservative treated wood is useful in new construction and renovations to prevent infestations. The European Community has issued a new directive regarding the use of wood preservatives (De Roma 2002).

Products such as boric acid, pyrethroids, silica gel, diatomaceous earths, and sodium octaborate tetrahydrate, formulated as dusts, are applied as spot treatments or into cavities created by insects in the wood. Dusts are efficacious against some wood destroying pests, e.g., carpenter ants and termites, and have long lasting residual activity when dry. Application of dusts can be labour intensive and require boring into the wood in the structure. Further work is needed to determine the efficacy of these products for other wood destroying insects. The use of arsenic and chromic compounds for pressure impregnation has several effects on the environment and human health, regarded as unacceptable in some countries.

5.5.8.3 Contact pesticides in structures

Surface application or space spraying (fogging, misting) of liquid residual pesticides is a part of most pest management programs in food production plants. Organophosphates, carbamates and pyrethroids are the classes of pesticides typically used. The target pests most often are stored grain insects, mites, psocids and cockroaches. When directed pesticide applications are made into the insect harbourage, infestations outside the product or raw commodity can be reduced. However, precise hand application is time consuming and expensive. Normally, residual applications are relatively easy to apply when compared to fumigation and can be effective for an extended period of time. Longevity of residual materials may be significantly influenced by surface composition, presence of other materials (such as dust, grease, food residues, etc.), temperature, humidity, etc. Some residual materials are repellent, causing insects to move to untreated surfaces.

Space sprays of contact insecticides usually involve dispersal of small particles below 50 microns in size dispersed in the air at a rate of 0.5 to 1.0 g m^{-3}. The small particles stay suspended in the air for a period of time and contact and kill exposed insects. It can supplement other control methods as part of an IPM program, but is seldom a complete control itself, since space sprays do not have penetrating ability and therefore cannot move between stacked bags or penetrate the bags where eggs and larvae are normally developing. Space sprays such as pyrethrins or dichlorvos have limited residual properties, which affects their ability to kill the insects not directly contacted (e.g., insects hidden in walls, floor drains, and other protected areas such as production machinery from which insect infestations can spread). Regulatory restrictions and actions within the U.S.A. and in many other countries may affect the continued availability of some organophosphate and carbamate insecticides, including those that are used as crack and crevice sprays or spot treatments inside milling, processing, and warehouse facilities. In the U.S.A., the food additive tolerance for dichlorvos is under review, thus in the future it may not be permitted where processed or packaged food will be contacted. This would effectively limit its use and its toxicity may lead to further restriction and unavailability.

5.5.9 Controlled and modified atmospheres, including carbon dioxide

Treatment with controlled and modified atmospheres (CA) based on a high content of carbon dioxide or nitrogen offers alternatives to fumigation for arthropod insects and vertebrate pest control in all durable commodities and was in effect used by ancient cultures in hermetic storage. This technique is still in use in various parts of the world (Varnava 2002). CA is also able to halt the growth of fungal pests but only while under gas. It is unlikely to be used for disinfestation where fast turn-around is necessary, unless combined with other factors such as high pressure (see Section 5.5.4) or raised temperature. The technology does require registration or other regulatory approval in some countries. Application of CA is constrained by the cost of the carbon dioxide or nitrogen required, particularly in developing countries.

Structures for use with controlled atmospheres must be well sealed to achieve effective levels and keep gas usage and expense to acceptable levels (Mann *et al.* 1997). Silo bins sealed to a standard suitable for recirculatory fumigation with methyl bromide are typically suitable for CA use. Well-sealed plastic containers also seem to be suitable for this purpose (Finkelman *et al*. 2002). The use of a continuous flow of controlled atmosphere, such as that provided by combustion of propane, can allow somewhat less gas tight enclosures to be treated (Bell et al. 1993, 1997a). Low oxygen atmosphere replacement and maintenance in floor-stored grain can be achieved with careful management. Care needs to be taken to avoid internal circulation of pockets of high oxygen, which can persist if sealing is too stringent (Bell *et al*. 2001). MBTOC has received information that carbon dioxide is now being used in the Netherlands as an alternative to methyl bromide for fumigating aircraft to control vertebrate pests.

Low oxygen atmospheres, created by adding the exhaust gas from a burner or nitrogen to a fumigation enclosure, need to reduce oxygen levels below 1% for effective action. Carbon dioxide atmospheres typically are applied at about 60-90% CO_2 in air. CO_2 has a toxic effect on insect pests and does not act just as an inert gas that reduces the oxygen level to below that supporting life.

Data on exposure times for control are available for many species and stages of stored product pests under particular sets of conditions (Annis 1987, Bell and Armitage 1992, Bell, 1996). Some new data is now available for *Callosobruchus maculatus* (Hashem 2000), and for *Cryptolestes ferrugineus* (Mann *et al*. 1999). Most species are completely controlled by exposures of 2 - 3 weeks at 25 - 30°C, or four to six weeks below that temperature. As an extreme case, larvae of *T. granarium* in diapause require exposures longer than 17 days at 30°C or less, with CO_2 levels at or above 60% in air (Spratt *et al*. 1985).

Controlled atmospheres are being increasingly used for insect control in artefacts (Gilbert 1991, Reichmuth *et al*. 1992, Rust 1996, Newton *et al*. 1996). Depending on the temperature, treatment may take two to eight weeks in a gas-tight chambers (Newton 1993). Controlled atmospheres with humidified nitrogen in a carefully constructed gas tight enclosure can control all stages of museum insect pests after purging to bring oxygen levels down to about 1%. Controlled atmosphere fumigation with 0.1% oxygen content, or atmospheres with more than 60% carbon dioxide are proving to be effective replacements for methyl bromide in museums (Strang 1996). An update on the use of CA and other options for pest control in museum artefacts was given by Reichmuth (2002).

The effective use of CO_2 is well established in some ASEAN countries where stored rice and other bagged commodities are treated (Nataredja and Hodges 1990, Sukprakarn *et al*. 1990, Annis and Graver 1990). The CO_2 CA system replaced a strategy of frequent methyl bromide fumigation and appears technically suitable for this wherever bagged grain is stored in warehouses long term and CO_2 is available at reasonable cost.

Methods for treating containerized cargo in transit with CO_2 have been described (Banks 1988). This is in use as an alternative to methyl bromide uses before shipment for some exports from Australia.

Until recently, use of CO_2-based atmospheres was preferred over nitrogen-based ones for bulk grain for various technical reasons. Recent developments in the on-site generation of nitrogen-based atmospheres have made these atmospheres more competitive in price and convenience (Navarro and Donahaye 1990, Banks *et al*.1991, 1993b, Bell *et al*. 1993, 1997a, Banks and Annis 1997). Nitrogen-based controlled atmospheres have now been in commercial use in Australia in an export grain terminal for more than 10 years. The bins were originally designed and equipped for methyl bromide treatments (Cassells *et al*. 1994). CO_2-based atmospheres are now in experimental use in Canada for treatment of grain elevators (Marcotte 1995). Propane or LPG also offers an economically competitive method of continuously generating a low oxygen atmosphere on site and has been successfully tested in France and the UK where loaded grain bins of over 1000 tonnes capacity have been held under a less than 1% oxygen atmosphere for treatment periods long enough to kill all pests (Fleurat-Lessard and Le Torc'h 1987, Bell *et al.* 1997a). Currently France has discontinued this use. Recent tests have explored the possibility of using propane burner exhaust gas to disinfest localized infestations or hot spots in bulk grain (Conyers *et al*. 2002).

Controlled atmospheres have been used to some extent to replace methyl bromide for disinfesting dried fruits and nuts and improved quality retention under CA may make CA treatments an attractive alternative to methyl bromide. Nitrogen-based CA can be effective in controlling rancidity as well as pests in some nuts. Johnson *et al*. (1998, 2002) demonstrated an integrated control method for walnuts, almonds and raisins that combined low oxygen disinfestation treatments with protective methods using pathogens, low oxygen or cold storage.

Apart from the recent development of using carbon dioxide with high pressure of about 25 bar (Prozell and Reichmuth 1991, Prozell *et al*. 1997), other prospects lie in the use of continuous flow systems for low oxygen atmospheres to treat sheeted enclosures and the use of raised temperature to treat commodities in chambers (Bell and Conyers 2002). The main change of using CA alone instead of methyl bromide would be the increase in the treatment period to 2 to 8 weeks depending on the temperature and species of the insect to be controlled.

Nitrogen-based CA treatments are being considered for quarantine rodent control between Barrow Island and mainland Australia for treatment of trucks and containers. The use of CA was recently reviewed by Adler *et al*. (2000).

5.5.10 Ethyl formate

Ethyl formate was formerly used as a fumigant for grain. Its use is now restricted to dried fruit and processed cereal products, and registration has lapsed in many countries. Registration has been applied for in Australia for grain. Annis and Graver (2000) have indicated that research conducted to date shows encouraging prospects for using ethyl formate in the grain industry in Australia.

The action of ethyl formate against pests of durable foodstuffs is rapid with control of many pests being achievable after exposures of only a few hours (Hilton and Banks 1997). However, the gas is highly sorbed by commodities, especially at raised humidity, and it is difficult to attain adequate distribution. Thus, in practice long exposure times may be needed to ensure adequate penetration of bulk commodities. Typical dosages on dried vine fruits are 3 to 6 ml per 15 kg. Ethyl formate can be corrosive to unpainted metals at high humidity. Ethyl formate has been demonstrated as not effective against immature stages of *Sitophilus oryzae* below 24°C, but effective against all stages of *Tribolium castaneum* and *Rhyzopertha dominica* (Damcevski and Annis 2000).

This compound is in use in some countries (e.g. Australia, South Africa) as a fumigant for packaged dried vine fruit at time of packing, directly substituting for the subsequent need for methyl bromide treatment soon after packing. A formulated as a formulation of 10% mixture in CO_2 has been produced in Australia to avoid possible flammability problems associated with using neat ethyl formate (Ryan and Pearson 2002).

5.5.11 Ethylene oxide

Ethylene oxide was used extensively to reduce microbial contamination in food commodities such as herbs and spices and some processed foods and coincidentally provides insect control. It was also formerly widely used for insect control on grain (Cartox system) and dates. Its use in these areas has been withdrawn in many countries, including the European Community, but it is still used in many other parts of the world, including China.

Because of its flammability, ethylene oxide is generally supplied in mixtures with inert diluents such as CO_2 or HCFCs. Ethylene oxide reacts with chemical constituents of some food commodities producing potentially carcinogenic compounds such as ethylene chlorohydrin.

Where health and environmental regulations permit, ethylene oxide may potentially replace methyl bromide in some non-food uses, notably treatment of some artefacts, manuscripts and other archive and museum materials.

Some countries still allow the use of ethylene oxide for pest control in foodstuffs. It is the fumigant of choice where sterilisation, as well as pest control, is required. Ethylene oxide is not usually recommended on herbs, vegetable seasonings or spice mixtures that include salt because of formation of chlorohydrin byproducts. Apart from methyl bromide, phosphine and ethylene oxide, there are no other fumigant gases currently used for pest control in these products.

5.5.12 Heat treatment

Heat treatment technologies are notable as a pest control option for durables that are capable of matching the speed of treatment afforded by methyl bromide and other fast-acting fumigants (Banks 1998). Commodities need to be heated to temperatures of 47 to 70°C and then rapidly cooled to avoid damage to heat-sensitive products. With very sensitive materials, humidity needs to be carefully controlled to prevent moisture content changes during both heating and cooling operations. The treatment time required is strongly dependent on the temperature reached and experienced by the target pest. All stages of stored product insects can be eradicated in approximately one minute when exposed at 65°C.

Heating can provide an alternative treatment method to using chemicals but also can synergise other treatments. For fumigants and controlled atmospheres it does this in three ways: by increasing the diffusion and distribution of gases and hence their powers of penetration, by reducing physical sorption and by increasing the toxicity or level of stress to target pests. Heat is particularly effective in increasing the efficacy of control using high concentrations of CO_2. At low CO_2 levels (10%) in air, however, the application of heat above 40°C may prove detrimental to efficacy; treatment times are actually longer than with heat alone (Bell *et al*. 2002a).

5.5.12.1 Heat treatment of durable products

A commercial technique employing heat and humidity to disinfest museum artefacts has been field tested in Germany (Adler and Rassmann 2000), Austria and the UK. Heat and cold treatments for artefacts have been reviewed (Strang 1992, Reichmuth 2002).

Pilot and laboratory studies on stored grain, reviewed by Sutherland et al. (1987) and Banks and Fields (1995), have typically used heated air at 90°C, or greater, as the heat transfer medium with the objective of heating the grain briefly to above 65°C. This high speed of action allows design of high throughput plants, such as those based on spouted or fluid beds for bulk grain (Claflin *et al*. 1984, 1986, Thorpe *et al*. 1984, Fleurat-Lessard 1984). Fluid-bed heating systems were developed to a commercial prototype stage, with treatment rates of up to 150 t h^{-1} (Evans *et al*. 1983, Thorpe *et al*. 1984, Fleurat-Lessard 1985, Sutherland *et al*. 1987), but large scale heat treatment facilities have not been developed for use at the typical handling speeds of large modern grain terminals, often 500 t h^{-1} or more on one belt (Sutherland *et al*. 1987).

On a smaller scale, Mourier and Poulsen (2000) have found that six seconds of exposure in a rotating drum connected to a natural gas burner with a grain inlet temperature of 300°C achieved 99% mortality of adult *S. granarius*; 40 seconds resulted in complete kill of all life stages without harming grain quality indicators. Stored product pest insects (all stages) can be eradicated in approximately one minute if they are exposed within the commodity to a temperature of 65°C.

Beckett and Wright (2000), using a spouted bed hot air system, showed that heating grain to a higher temperature for a short period is more effective for insect control than using lower temperature for a long period. Mahroof and Subramanayan (2001) showed that the efficacy of insect control depends not only on the temperature but also on the rate of increase on temperature.

As an alternative to heated air, many early studies have been carried out on the use of rapid heating of grain by microwaves, and more recently radio frequency radiation (Nelson *et al.* 1998, Wang *et al.* 2002). The use of infrared radiation for heating grain has also been proposed (Ingemanson 1997, Sanchez-Hernandes *et al*. 2002). Recent tests indicate that selective heating of the infesting insects in stored grain increases non-linearly at frequencies above 10.6 Ghz and that relaxation processes associated with free water in the insect and increased energy transfer at frequencies 24 Ghz would produce enhanced selective heating (Halverson *et al*. 1996, 1997). Halverson *et al*. (1997) reported studies of both static (batch process) and dynamic (continuous process) applications to develop systems capable of dealing with a throughput of up to 24 tonnes of grain per hour. A prototype full-scale facility has now been developed (Halverson *et al*. 2001, Phillips *et al*. 2002).

Heat disinfestation is one of the very few potential alternatives for disinfestation of bulk grain from live snails (*Cernuella* and *Cochlicella* spp.) (Cassells *et a*l. 1994). Current recommendations against these quarantine pests involve high dosages of methyl bromide (Bond 1984). Heat also has the potential to replace methyl bromide treatments for some quarantine disinfestations targeted at *Trogoderma granarium*, an important quarantine pest of grain (Rees and Banks 1998), and other species of *Trogoderma* (Wright *et al*. 2002).

Under good process control there is no damage to the end use qualities of treated cereals at levels of heating required to eliminate insect pests. These include bread-making quality of wheat, rice quality and malting quality of barley (Fleurat-Lessard 1985, Sutherland *et al.* 1987). However, the margin of error is small and only slightly excessive treatment can cause some adverse effects (Fleurat-Lessard and Fuzeau 1991).

Brief heat treatments have potential to disinfest cocoa, coffee and specific dried fruit, nuts, seasonings and spices. Techniques will need to be researched carefully before adoption to determine effects on quality of the treated product. It is already known that high temperature storage or treatment of many dried fruit and nuts can lead to detrimental colour change or rancidity. Heat combined with CO_2 can control insects in stored dates (Case study 24).

The tobacco industry has long practised pest control procedures based on heat (Samfield and Brock 1958, Ryan 1995). The lethal effects of a range of exposures of extreme temperature to adults, pupae, four-week-old larvae, two-week-old larvae and eggs of the cigarette beetle, *Lasioderma serricorne*, have been investigated (Meyer 1980). At 50°C the lethal exposure for larvae (the most tolerant stage) was 3 hours while at 55°C an exposure of 1 hour was lethal. Heat is used in the redrying process for tobacco prior to storage, followed by steam to supply the exact amount of moisture required, but this process requires some additional action to eliminate all survival (Tenhet and Bare 1946). Vacuum-steam conditioning is effective, a "steamed" tobacco temperature of 60°C for three minutes being sufficient to kill all pests (Ryan 1995). All processes rely on the ability to limit the throughput of samples for treatment and are unsuited to deal with a sudden large outbreak of infestation.

5.5.12.2 Heat treatment of structures, including mills

Heating to greater than 44°C is reported to eradicate drywood termites. Higher temperatures are likely to give more rapid mortality but the limiting factor with regard to treatment time is expected to be the rate at which lethal temperatures are attained throughout the treated structure. Further study is needed to determine what specific structural components and contents are affected by heat, and how these may be protected, and the quantity of energy required to attain eradication in practice. Whole-structure heating for controlling drywood termites was first reported several decades ago (Ebeling 1975). However, laboratory and large-scale field validations have only recently been reported (Lewis and Haverty 1996a). Whole-structure treatments with heat appear to be effective. However, unsuccessful control using heat can be due to the occurrence of heat sinks. Heat sinks are areas within a structure that are more difficult to heat, for example, wood on concrete (Lewis and Haverty 1996b). Pre-treatment preparations to prevent and minimize structural and household item damage from heat treatment have been reported (Ebeling 1994).

Heating above 50°C for 20-30 h has been used to control insects in flour mills for almost 100 years. It is increasingly used by a number of major food processors as an important part of their pest control programme (Case study 27, Heaps and Black 1994, Clarke 1996, SFT 1997, Adler and Rassmann 2000, Hofmeir 2002). Food plants that can be successfully heat-treated rarely, if ever, require fumigation. It is also advantageous in that there are no residues and treatments are as just quick to perform as with methyl bromide. The application of inert dusts in voids and harbourages can enhance efficacy and lower target temperatures (Fields *et al*. 1997). In some situations, however, heating can pose problems. The siting of mills near heat sinks such as rivers and water fronts can prevent target temperatures from being achieved in certain regions and particularly in mills without internal heating systems heating costs can be high (Lindberg 2001, Fields and White 2002).

Although expansion of use of this technique is expected, there are other important considerations. For example, some structures cannot tolerate the stresses caused by extreme changes in temperature and differential expansion of structural components, e.g. of concrete and steel. In larger structures, the principal problem is one of achieving a uniform distribution of heat. Insects can sometimes migrate temporarily to outer walls or floor drains and successfully escape the effect of heat treatment. Some equipment must be modified or removed to avoid damage. Some greases may liquefy and must be reapplied after heat treatment. Some products cannot withstand the required temperatures and may have to be removed and treated separately to prevent the reintroduction of pests.

Heat treatment technologies are notable as one of the very few pest control options that are capable of matching the speed of treatment afforded by methyl bromide and other fast-acting fumigants. The time required is strongly dependent on the temperature reached and experienced by the target pest.

5.5.13 Hydrogen cyanide

Hydrogen cyanide has been used as a fumigant for almost a century and still has some uses in a few countries. It was previously used widely as a fumigant for durable commodities, museum specimens, and in mills and other structures. Historically it has been used for long-horned beetles and other wood destroying insects. Largely, it has been superseded by methyl bromide and phosphine, both of which are more convenient, less expensive, and, in many cases, more effective to use. Modern instructions for use of HCN are given in Anon. (1989). These relate particularly to the ASEAN region, but are, in principle, suitable for most countries.

Recent studies by Rambeau *et al*. (2001) have demonstrated that *ct*-products as low as 5 g h m^{-3} are effective against all stages of *T. confusum, T. castaneum, Ephestia kuehniella* and *P. interpunctella*. Consequently, these authors have proposed that HCN could be used as an immediate replacement for MB for empty structures in countries where the chemical continue to be registered, including France, Germany, Austria, Switzerland and Central European Countries.

Availability of HCN may be limited by its extreme acute toxicity, lack of registration in most countries and regulations on its transportation and handling. Cylinders of liquid HCN are unstable and cannot be stored for long periods. However, HCN can be developed in situ from sodium cyanide (Anon. 1989). It acts quickly against rodents and their ectoparasites, particularly fleas. Hydrogen cyanide is used in aircraft for control of rodents, insects and other pests in several countries. It can also be used with high efficacy for pest control in artefacts. The Codex Alimentarius approved limits for HCN residues in grain and flour have lapsed due to lack of governmental support.

The alternatives currently available for ships include HCN, used against rodents in Singapore and France, phosphine, used against both insects and rodents elsewhere, and rodenticides and traps. HCN could be used in empty vessels alone where there is no water in the bilges. HCN has some advantages in the control of rodents because it rapidly kills them and their ectoparasites, principally fleas.

5.5.14 Inert dusts

Inert dusts may be: clays, sands, ashes or earths; diatomaceous earths (fossilized remains of diatoms consisting mainly of silica with small amounts of other minerals); silica aerogels (very light, non-hygroscopic powders that are effective at lower dosages than diatomaceous earth (DE) formulations); and non-silica dusts, such as phosphate and lime. Some inert dusts are widely used as food and processing additives and others are accepted for use on foods certified as 'organic' in some countries.

DE products have also long been used as carriers for insecticides, but now new formulations being produced that are intended for use alone. These formulations are being designed to minimize their abrasive properties (to protect conveying machinery) and enhance their insecticidal action as desiccants by promoting their capacity to selectively absorb insect cuticular waxes. Inert dusts are rapid in their lethal action under favourable conditions for most pests (Mewis and Ulrichs 2001, Arthur, 2001). They lose effectiveness at humidities above about 75% RH (Le Patourel 1986). *Trogoderma* species do not appear to be effectively controlled. Some tolerance to inert dusts may be linked to slow movements by insects or by their ability to avoid treated grain (Rigaux *et al*. 2001).

Korunic *et al.* (1996) summarise the uses and properties of new DE formulations that overcome many of the problems formerly associated with this technology.

5.5.14.1 Uses on commodities

Inert dusts have a long history of use for grain protection (Ebeling 1971, Golob and Webley 1980, Quarles 1992ab, Arthur 2002ab) and more recently have been evaluated as protectants for legumes (Giga and Chinwada 1994, Prasantha and Reichmuth 2002). Several of these inert dusts are registered in some countries for these uses (Banks and Fields 1995, Erb-Brinkmann and Straube 2002). They are particularly useful for pest control in dry conditions, either in storage structures (Fam *et al*. 1974), or, for example, to provide protection against insect infestation in dry grain stored long term for animal feed (Desmarchelier and Dines 1987). Dryacide, an activated DE, is in widespread use in Australia in the grain handling industry.

Inert dusts do not require capital equipment, are relatively non-toxic, provide continued protection, and do not affect baking quality (Desmarchelier and Dines 1987, Aldryhim 1990). Their disadvantages are decreased flowability of grain, visible residues that can affect grading, and decrease in the bulk density of grain, although newer formulations alleviate these problems. They can cause excessive wear in handling machinery and may give rise to dust problems in the workspace. To alleviate dust problems, inert dusts can be applied as aqueous slurry for surface treatment, though this can reduce effectiveness (Maceljski and Korunic 1971). Research is on-going in relation to new methods of application (Fields et al. 1997).

Recent reviews summarize tests conducted with different formulations of DE as grain protectants (Golob 1997, Korunic 1998). Variations in the source of the DE, physical properties, and insect pests species can all influence toxicity and efficacy when commercial DE products are used as grain protectants (Fields and Korunic 2000). Increases in relative humidity and grain moisture content are directly correlated with decreases in efficacy (Fields and Korunic 2000). However, even in damp climates such as the UK DEs have been shown to be suitable replacements for organophosphorus insecticides in protecting grain (Armitage *et al*. 1999, Cook and Armitage 2000, 2002).

5.5.14.2 Inert dusts in structures

Various forms of diatomaceous earths (DE) have long been used as stored product protectants with various effectiveness and product quality effects (Banks and Fields 1995, Ebeling 1971). Several DE formulations are being used to assist in controlling structural pests (Quarles and Winn 1996). Some of these are very effective at low application levels (Korunic and Fields 1995, Fields *et al*. 1997). In recent studies in Canada, Fields *et al*. (1997) combined a DE formulation with heat treatment, resulting in greater mortality at lower temperatures, and conducted a field trial in a commercial plant during their regular heat treatment. Dry application of a DE gave 100 % mortality of the confused flour beetle adults after 13-22 hours and 41^{o}C compared to untreated insects that required 32-38 hours at 46-47^{o}C (Fields *et al*. 1997). The results of this field trial are now in commercial application in a Canadian flour mill with good results (Bergen 1997). Until recently, there were few published reports regarding efficacy of DE used as a contact insecticide on flooring surfaces inside buildings. In new tests where adult red flour beetle, *Tribolium castaneum*, and adult confused flour beetle, *T. confusum*, were exposed to commercial formulation of DE, toxicity generally increased with temperature and decreased with relative humidity (Arthur 2000a). However, when these beetle species were provided with a flour food source either during or after exposure to the DE, there was a dramatic decrease in product efficacy (Arthur 2000b). Similar results were shown in other studies in which the same species were exposed to kaolinite-based particle film, another type of inert dust (Arthur and Puterka 2002).

Further research should be undertaken to determine the potential of inert dusts in providing residual control in cracks and crevices. Subramanyam and Roesli (2000) have provided a comprehensive review of the current status of inert dusts in pest control, including a summary of future research needs.

5.5.15 Insect growth regulators

Insect growth regulator (IGR) is a collective term used to identify several groups of chemicals that interfere with the growth and development of insects. Generally, they have low toxicity to vertebrates (Menn *et al*. 1989). IGRs are generally used in a similar way to contact insecticides and are subject to the same constraints. Additionally, they are relatively costly and are not normally directly toxic to adult pests: both of these factors limit their uses.

The actions of IGRs can target one or more developmental stages in the insect and can affect one or more metabolic sites that are essential to the completion of its life cycle. Some of the first IGRs developed were juvenile hormone (JH) agonists, which act by maintaining the juvenile characteristics of the immature stages, thus preventing metamorphosis into the adult. If administered to the adult, the JH agonist can interfere with one or more reproductive functions. Early introduction into the egg, either via the adult before egg laying or by contact with a treated surface after egg laying, disrupts embryonic development, preventing egg hatch (Mkhize 1993, Dyby and Silhacek l997). At lower agonist levels, egg hatch occurs normally but mortality at each of the subsequent larval moults and the pupal moult occurs because of abnormal shedding of the old cuticle. The potential of IGRs for pest control in storage was reviewed by Oberlander *et al*. (1997).

Methoprene has been registered for use in the protection of a variety of stored commodities in a few countries, including the U.S., Australia, and the U.K, especially for tobacco, a non-food use. It is effective against many stored product pests, including *Lasioderma serricorne, Rhyzopertha dominica, Ephestia cautella, Plodia interpunctella, Trogoderma granarium*, and *Oryzaephilus surinamensis*, but not against *Sitophilus* spp. (Snelson 1987, Mkhize 1986). A related material, hydroprene, is registered for application as a surface treatment in the USA (Arthur 2002b).

The juvenile hormone analogue, fenoxycarb, has shown potential as a grain protectant (Edwards et al. 1991). Recent studies with moths (Monconduit and Mauchamp 1998) indicate that very low level (ppb) treatments with fenoxycarb of the egg or larvae just after hatching causes lethal disruption of moulting throughout the larval period. In these studies, virtually none of the insects survived to the pupal stage. Although this study is useful in showing the potential of IGRs for management of stored product insects, fenoxycarb is unlikely to be registered because of long persistence of residues and potential toxicity concerns.

Other chemicals that have been classified as IGRs include chitin synthesis inhibitors, ecdysteroid agonists and neem seed extract. Some of these are approved for use in specific applications, but their use in food preparation areas and on food products has been slow to develop because of cost, unfamiliarity with their mode of action and possible health concerns. However, progress has been made in the registration of JH agonists for food applications. In the USA, a tolerance of 0.1 ppm has been established for pyriproxyfen "on all food items in food handling establishments where food and food products are held, processed and/or prepared". Model warehouse tests indicate that pyriproxyfen can also be effective in protecting packaged cereal products from moth damage during long-term storage (Oberlander and Silhacek 2000). In Israel attention has recently been focussed on the chitin inhibitor, Novaluron. On wheat, 95% control of *S. oryzae* and *R. dominica* and complete control of *P. interpunctella* and *T. castaneum* were achieved in laboratory tests (Kostyukovsky *et al*. 2002).

Studies with moths (Dyby and Silhacek 1997, Monoconduit and Mauchamp 1998) indicate that with treatments in the parts per billion range pyriproxyfen, applied to eggs or newly hatched larvae, causes lethal disruption of moulting throughout the larval period. Embryogenesis and moulting appear to be two developmental processes especially susceptible to this JH agonist and should be targeted in new control methodology. Agonist intervention during early in development has the added advantage of very minimal damage to the infested commodity.

5.5.16 Integrated Pest Management

Any integrated pest management (IPM) programme must begin with identification of existing and potential pests, the cause of their presence, their vulnerabilities, and consideration of all practical chemical and non-chemical controls with adequate consideration of materials present, worker safety and the environment. Some integrated pest management (IPM) strategies require constant maintenance in order to succeed. Occasional full-site or curative treatments may be required to supplement IPM programs. These may involve fumigation, possibly with methyl bromide, or other processes.

With the above reservation, the IPM approach, employing a variety of tools and techniques, both non-chemical, which were recently reviewed by Hagstrum and Subramanyam (2000), and chemical, will be the key strategy to replace the use of methyl bromide in stored products and in structures. Action thresholds of pests should be determined for the situation, pest and commodity as reviewed by Subramanyam and Hagstrum (1995). Assessment of the actual or potential pest problem will require continual inspections of the facility to determine the intensity and distribution of a pest problem. This will guide treatment schedules and determine the effectiveness of the overall strategy.

In developing an IPM plan, consideration may need to be given to building design improvements, the materials present, retrofitting of certain facilities and effects, and exclusion practices aimed at reducing or eliminating infestations in incoming food and ingredients. The plan will also require implementation of good sanitation practices, with co-operation between cleaning crews, quality control officials and pest control contractors, as well as the development of a continuous inspection and monitoring program. Pest minimization must become the responsibility of everyone in the facility, in the same way that quality control is assured. It can be seen that a long lead-time is needed to establish the full IPM program.

In implementing the plan, physical and chemical controls will most likely be required. This IPM approach has been introduced for food and flour processing facilities in many countries (Case studies 26,27, Anon. 1995ab, Nielsen, 2000). Some have eliminated regular treatments with MB and other fumigants, while others have reported substantial reductions in their use of fumigants. The Canadian Methyl Bromide Industry Government Working Group (1998) has prepared an IPM strategy guideline for use in food processing facilities. Adoption of these practices in Canada is becoming common (McCarthy 1998, Stanbridge 1998).

An important part of IPM use in facilities is to identify the infested area, such as by use of spatial analysis. In this process, a grid of traps is placed within the facility and is monitored. The trap catches are precisely plotted on a map over a set period of time. This allows the pest management professional to pin-point the infestation and target the treatment to the specified area in bulk grain, processing plants, warehouses, and retail stores and reduces the need for broad scale application of fumigants or other insecticides (e.g. Brenner *et al*. 1998, Arbogast *et al*. 2000). The contour maps generated are also useful in evaluating the effectiveness of control intervention and in providing documentation of pest problems and their mitigation.

IPM requires understanding of the interactions that occur between stored-product insects and their storage environment. Mathematical modelling provides a unifying framework that ties effects of various environmental factors together and permits us to evaluate their relative importance in determining population behaviour (Throne 1995). These models form the backbone of expert systems designed to assess risk and recommend control interventions (Flinn and Muir 1995), and they can be applied to establishing economic thresholds.

Monitoring for insect infestation can be done either directly, by examining premises and products for insects, or indirectly by monitoring indicators of infestation that include monitoring temperature and carbon dioxide. Direct methods include visual inspection, examining samples of a product, and trapping with or without pheromones or food attractants. Research over the past two or three decades has produced a variety of traps that are effective in detecting insects in bulk commodities, processing plants, and warehouses (Cogan *et al*. 1991, Mullen 1992, Vick *et al*. 1990, White *et al*. 1990), but research is needed to relate numbers of insects captured to economic action thresholds (Arbogast and Mankin 1999). A new generation of traps, which will count insects electronically as they are captured, is now being developed (Epsky and Shuman 2001).

A major component of any IPM system for processing, storing, and marketing durable commodities is sanitation or 'hygiene', which generally involves application of measures to remove pests or to deny them access to structures or commodities. These measures include redesigning and modifying buildings and machinery to eliminate harbourage for pests, cleaning and removal of food residues in which pests could multiply, and regular monitoring. Raynaud (2002) described the significant impact of intensive sanitation on the reduction of the infestation pressure by stored product insects. Good warehouse practices, such as stock rotation, and use of insect resistant packaging where practical, reduce the probability of infestation. Other measures, such as application of insecticide sprays, may sometimes be needed to prevent movement of pests into stored products (Banks and Fields 1995).

The Canadian Conservation Institute (Strang 1996) has developed an IPM programme for Canadian museums, libraries and similar repositories. A comprehensive IPM strategy involving infestation detection, isolation, localised treatment and phosphine fumigation is in use for tobacco in many facilities (Ryan 1995). The dried fruit industry include use of permanent sheeting over carton stacks of dried vine fruit combined with hygiene and a disinfestation treatment, e.g. CO_2 or phosphine, or use of cooling and CA in a sealed system for nuts. Also, efficient sorting machines, removing damaged or infested nuts could be used in combination with sanitation and packaging, and beneficial insects (predators), to give an acceptable level of control. High efficiency sorting machines may be used together with protectants and/or physical treatment to provide acceptable control levels. Beneficial insects might be used for space treatments and sanitation.

In the U.S. and other countries, IPM systems have long been in place for milling and food processing companies with particular emphasis on sanitation and insect detection. As currently used, this process has often not achieved adequate control levels without periodic general infestation treatments, but there are some recent positive results from Denmark (Nielson 2001). Methyl bromide is still widely used in some countries as a disinfestation treatment although heat treatment is becoming more common.

Many IPM strategies would benefit from engineering research in order to be applied efficiently. New methods of application, increased energy efficiency, and sealing methods for existing or new structures need to be identified or developed. Specific facilities may need to be designed for use of multiple technologies particularly for the use of heat as a disinfestation treatment.

5.5.17 Irradiation

Irradiation is a broad-spectrum method of controlling pests. The technique can be used as an alternative to methyl bromide for several durable commodities and is already in extensive use for disinfection of herbs, spices and herbal products; disinfestation can be a side benefit of disinfection treatment. The process involves the use of gamma energy, accelerated electrons or X-rays to penetrate the commodity.

Disinfestation by irradiation has a long history (since 1912) and a sizeable research investment. Brower and Tilton (1985) and Tilton and Brower (1987) summarised the radio-sensitivity data on forty stored-product pest species beetles are more sensitive than moths, and fruit flies are more sensitive than beetles. Mites have a range of sensitivity similar to that of beetles. Irradiation is effective at all temperatures with either bulk or bagged commodities. The principles of this method have been described previously (MBTOC 1995, 1998).

The International Consultative Group on Food Irradiation (ICGFI), under the aegis of the FAO/IAEA Joint Division, has published provisional guidelines for the irradiation of foodstuffs for insect disinfestation as recommendations to be followed when using the technology (ICGFI 1988).

The method is approved for at least one food use by 41 countries, although in less than 25 of these are primarily for disinfestation purposes (Anon. 1998). The regional members of the International Plant Protection Conventions (IPPC), including the North American Plant Protection Organization (NAPPO) have recognized the effectiveness of irradiation as a broad-spectrum phytosanitary treatment (Marcotte 1996, Griffin 1996).

In Indonesia, commercial quantities of bagged rice have been irradiated as part of government rice storage. It is an effective treatment against *Sitophilus* species.

Irradiation has been shown to control pests of cocoa or coffee beans, dried fruits and nuts (Appiah *et al*. 1981, Kader *et al*. 1984, Hoedaya *et al*. 1985, 1987, Manoto *et al*. 1987), but the technique is not used commercially at present. Irradiation does cause off flavour in walnuts above 0.9 kGy (Rhodes 1986). Johnson (1995) found radiation potentially useful for quarantine treatment of walnuts.

For both walnuts and dried fruits, use of irradiation to disinfest packaged product holds more promise. Because the amount of product to be treated would be spread over a longer period of time, smaller on-site irradiators or remote contract irradiators could also be effectively used for outgoing packaged product. Irradiation also has promise for use as a phytosanitary treatment. Need for this treatment would be limited to product exported to certain countries and the amount of treated product would be reduced. Here, processors would be unlikely to use on-site irradiators; units located at ports or contract irradiators would be more efficient.

Irradiation has been used to disinfest dried fish in Bangladesh and the Philippines (Matin and Bhuia 1990, Manoto *et al*. 1985). Irradiation studies on cigarette beetle, *Lasioderma serricorne*, indicated that a dose in the range of 0.6 - 1.0 kGy can control all developmental stages. A dose of 5.0 kGy had no effect on nicotine content, volatile oil content, composition or pH of tobacco (Hoedaya *et al.* 1987) but radiation techniques are not presently used in the tobacco industry.

5.5.18 Mechanical methods

Many situations in which agricultural products are mechanically conveyed during food processing offer the opportunity for control of insects by shock, abrasion and impaction. Within an IPM system, other mechanical methods such as screening and sorting offer the potential to reduce the need for methyl bromide (Banks and Fields 1995). Screening and sorting measures are designed to remove pests or prevent their access to the product or commodity. Systems have been designed to separate out infested grains by projection through air or by aspiration technology.

The rice milling process which subjects rice grains to violent shaking without breaking the kernels, contributes substantially to insect control, a recent study demonstrating 98% control of rice weevil stages (Ducom-Gallerne and Vinghes 2001).

In flour mills screens and sifters remove dockage, insect stages and fragments from the production line. A further level of control of insects is achieved through the use of impact machines such as the “Entoleter”. The principle of the Entoleter was developed over 60 years ago for use in the flour milling industry (Cotton and Frankenfeld, 1942) and such machines are now a routine fixture in flour mills (Plarre 2000). In the Entoleter, flour falls between two rapidly spinning discs. Centrifugal force pushes the flour to the edges of the discs where it impacts a row of steel pegs mounted on the rims, and is thrown against the outer steel casing before falling into the basal receiving hopper.

Working with moving grain, Loschiavo (1978) found that dropping of adult insects into free flowing grain caused substantial mortality. Moving grain pneumatically or by screw auger has also been shown to reduce the number of free-living stored product insects and mites (Bahr, 1991, White *et al*. 1997). Flour passes through a vacuum cleaning system caused between 72 and 100% kill, depending on the species, of all developmental stages (Bahr 1991). Free-living insects prove easier to control than those developing inside the grain. Subjection of grain to impaction machinery could not eliminate internal grain feeders below levels causing damage to the grain (Bailey, 1962, Stratil *et al.* 1987). In studies on bruchid infestation of beans, Quentin *et al*. (1991) found that gentle tumbling of beans every 8 hours over a two week period reduced population growth by 97%. The effect was explained by prevention of first instar larvae from entering the seed after egg hatch. The use of disturbance and impaction techniques merit further experimentation and development in the field of insect control.

5.5.19 Other fumigants

There are many compounds that have been considered as fumigants at one time or another. Those currently under active investigation are as follows.

5.5.19.1 Cyanogen

Cyanogen is under consideration as an alternative for control of insects and fungi in timber and for fumigation in flour mills in Australia (Viljoen and Ren 2002, Ren 2002). It has been patented for these uses.

5.5.19.2 Methyl iodide

This related compound has properties similar to methyl bromide as to efficacy and does not have an ozone-depleting potential, but is more expensive to synthesize. Currently, a registrant is pursuing registration in the US on the strength of its potential for use on soil. Some activity of methyl iodide against stored product pests has been reported in the literature (Soliman and Kashef 1962, Kostjukovsky *et al.* 1997).

5.5.19.3 Methyl isothiocyanate (MITC)

MITC was introduced in 1959 by Schering AG as a soil nematicide under the trade name Trapex. This compound is being studied as a grain fumigant and protectant (Ducom 1994). Preliminary studies of biological efficiency showed that MITC is very active against *Sitophilus granarius* (all stages) at a low *ct*-product of 8 g h m^{-3}. For optimal results, this compound has to be very well mixed with the grain because it is highly sorbed. Recent research indicates that it will be more useful as a treatment method for perishables (Ducom and Vinghes 1997).

5.5.19.4 Methyl phosphine

Methyl phosphine has been investigated primarily as a counter measure to phosphine resistance, but also has the potential to replace some other methyl bromide applications. Methyl phosphine has specific action against phosphine resistant strains, being more toxic to these than to susceptible strains, and thus could replace uses of methyl bromide in the combating of resistance (Chaudhry *et al*. 1997*)*. It is, however, an unstable compound and requires further research to evaluate its true potential.

5.5.19.5 Ozone

This gas has a sterilising action against bacteria and viruses. Following on from some earlier information on the toxicity of ozone to *Sitophilus oryzae* and *Oryzaephilus surinamensis* (Yoshida 1975), *Tribolium* spp. (Erdman 1979), *Ephestia elutella* (Mills 1992), and the moulds *Aspergillus flavus* and *Fusarium moniliforme* (Mason *et al*. 1997), further tests have been carried out but with mixed results. Kells *et al*. (2001) found high (>90%) activity against adult *T. castaneum* and *S. zeamais*, and *P. interpunctella* larvae, and moderate activity against *Aspergillus parasiticus* in stored maize. Less complete control was reported by Leesch (2002) and Zhanggin *et al*. (2002).

5.5.19.6 Propylene oxide

Propylene oxide is in use as a disinfection agent for nut meats and some other commodities in the US and has recently been subjected to renewed investigation as an insecticidal fumigant (Griffith and Warren 2001). Both alone and at reduced dosage in combination with CO_2 or vacuum it can effectively control pests (Isikber *et al.* 2001, 2002).

5.5.20 Packaging and exclusion

Packaging of finished food products is a vital aspect of infestation prevention and can avoid the need for subsequent fumigations in the warehouse. The package should be designed to protect the product from the point of manufacture to the time it is consumed, an interval that can be as long as several years (Mullen and Pederson 2000). Insect pests with a known ability to penetrate paper and polythene packaging include the beetles *Rhyzopertha dominica*, *Lasioderma serricorne*, and larvae of the moths *Plodia interpunctella* and *Corcyra cephalonica*. Many other stored product pests are opportunistic in entering packages through tiny gaps and imperfections in the seal. Packaging needs to be designed to avoid as far as possible folds and glue seals need to avoid channels and overwraps. Use of materials acting as a barrier to the escape of food volatiles or odours are helping in minimising pest attraction. Alternatively the use of a repellent such as methyl salicylate can be incorporated in the packaging. Another option is packaging under modified atmospheres. Shrink wrapping provides the means for such an atmosphere to develop by natural processes. This approach closely resembles the principle of hermetic storage used for storage of cereal and other crops, an area which, together with use of vacuum, has recently had renewed focus as a research topic (Sabio *et al*. 2000, Navarro and Donahaye 2000, Navarro *et al*. 2001, 2002).

Insect-resistant packaging has been shown to be an effective alternative to methyl bromide fumigation for processed grain products in consumer-sized packages. The increased use of plastics and improves seals have been shown to be effective in reducing infestation in dry pet foods, breakfast cereals, flour, rice products and infant cereal (Mullen and Mowery 2000). Many packages can remain insect resistant if holes are smaller than 0.24 mm. The use of odour barriers can enhance resistance. Insect-resistant packaging can reduce the need for MB or other insecticidal treatments as part of an IPM approach.

Exclusion using cotton sheets over stacks of rice is a useful component of an IPM system for stored rice protection in S. E. Asia (Case study 22)

5.5.21 Pheromones

Pheromones are chemicals produced by one member of a species that are transmitted externally to and influence the behaviour or physiology of another member of the same species. The most fully studied of this class of semiochemicals are the sex pheromones. In most cases the female releases a chemical into the air that both attracts and sexually stimulates males. The sex pheromones of several storage-related pests, both beetles and moths, are among the earliest identified pheromone molecules (Mayer and McLaughlin 1990). The use of pheromones in the food industry has been reviewed (Phillips 1997).

Pheromones can be used as trap baits to monitor for stored product pests or they may be employed as direct control agents via mass trapping, pathogen dissemination or mating disruption (Burkholder 1985, Burkholder and Boush 1974, Shapas *et al*. 1977, Fleurat-Lessard 1986). Trematerra (1994ab) summarizes studies from 1986 to 1992 to use mass trapping, mating disruption and an attracticide method (combination of insecticide with attractant bait) to control Mediterranean flour moth in flour mills. Pierce (1994) describes the use of pheromone trapping to locate and suppress infestation in Hawaii. All of these techniques demonstrated suppression, but not total disinfestation. Better results were obtained against a localized infestation of a warehouse moth in a cereal processing facility (Nickson *et al*. 1998).

The primary sex pheromone component of the phyticine moths is highly susceptible to degradation when exposed to light or air. Recently, Shin Etsu 'rope' formulations of this chemical have been used to disrupt mating of Indianmeal moth in a warehouse. Indications are that mating disruption is useful as a control technique only with low or localised populations.

The registration procedures for control systems based on pheromones for stored commodities need clarification.

The potential for use of pheromone traps as an effective monitoring tool has been enhanced by the development of new traps. Traps such as the Flite-Trak M2 (Mullen 1992) and its more dust resistant modification, the Dome Trap, have been proven to be effective for monitoring beetles in storage, processing and retail stores. The SP Locator moth trap has a reduced pheromone load that makes it effective for monitoring in areas where a short-range attraction is desirable. The Discreet Trap (Mullen and Dowdy 2001) was made to be hidden from view and has become widely used in retail stores where it is desired to have traps out of the sight of customers. It is effective for the Indianmeal moth and cigarette beetle. Platt *et al*. (1998) used traps to survey insect populations in grocery stores to increase the awareness of employees and management of the need for effective IPM practices.

The development of effective traps will contribute to the potential of the use of pheromone-baited traps to eliminate insect infestation in food premises and are an important tool for spatial mapping to locate infestations. Trematerra (1994ab) and Nickson *et al*. (1998) have used trapping to reduce moth infestation levels below economic thresholds.

5.5.22 Phosphine

Phosphine is the only fumigant, other than methyl bromide, which is widely registered for disinfestation of durable commodities. It is the only available in-kind alternative extensively in use, principally for cereals and legumes. It has the potential to act as a one-for-one substitute for methyl bromide in many situations, but can also act as a component of an IPM process to avoid methyl bromide use. It ranks as one of the most toxic fumigants known, but is used at low concentrations. Its action against pests tends to be much slower than methyl bromide, with long exposures required, particularly under low temperatures. The use of phosphine is generally not recommended below 10^{o}C or even 15 ^{o}C in some countries. Depending on temperature and humidity, fumigations with phosphine require five to 16 days for full effectiveness, in contrast with one day under gas for methyl bromide.

There are many publications describing application of phosphine to stored grain and other durable commodities (e.g. Bond 1984, Banks 1986).

Phosphine penetrates well into commodities and can be removed rapidly by aeration after treatment. It has a low degree of sorption by most commodities at low water activities. Phosphine will form an explosive mixture with air when the concentration exceeds 1.8% by volume at normal atmospheric pressure. This level would not be reached in normal fumigation practice. This limit reduces at reduced pressure and care needs to be taken in designing recirculation and vacuum systems in chambers if phosphine is to be used (Green *et al.* 1984).

Phosphine reacts with copper, silver and gold, and in some situations this may preclude its use. Brigham (1998) studied the corrosion of several metals at various phosphine concentrations at different temperatures and humidities. This is especially critical with regard to corrosion of electrical equipment (Bond *et al*. 1984, Rislund 1996, Brigham 1997), but there are actions that can be taken to lessen these effects in many situations. For example sensitive items within the treatment enclosure have been protected by supplying positive pressure from an outside air or carbon dioxide source (Mueller 1996).

Various proprietary formulations of phosphine are available world wide. Most contain aluminium phosphide or, less commonly, magnesium phosphide, formulated with ammonium carbamate or urea to lessen the risk of flammability. Phosphine is generated *in situ* by the reaction of atmospheric moisture with the metallic phosphide (Bond 1984). There have been a number of studies to improve the delivery of phosphine within a commodity (e.g. Taylor and Harris 1994). Phosphine generated from metallic phosphides is produced slowly and unevenly and the concentration produced has proved impossible to control with any precision. Some new formulations of phosphine are being produced that are more controllable (Reichmuth 1994, Waterford and Asher 2001). New phosphine generators have been developed in

Chile, Japan, China, Germany, India and Australia (Horn 1997, Kawakami 1998, Sen *et al*. 1999, Waterford and Asher 2001, Mathews and Luzaich 2002), and phosphine formulations in cylinders at about 2% w/w in CO_2 (Winks 1986, Chakrabarti *et al.* 1987, Chakrabarti 1994) or nitrogen ("Frisin", Messer Griesheim GMBH, Germany) have been developed, increasing the competitiveness and effectiveness of phosphine use compared with methyl bromide. The 2% mixture of phosphine in carbon dioxide (ECO_2Fume) and an application system for bulk grain is widely used in Australia (SIROFLO®) (Winks 1990, 1993).

The new non-flammable cylinder-based formulations provide potential for lower dosages and more accurate application of phosphine than other phosphine producing methods. However, corrosion risk and potential for resistance development remain though some of the corrosion risks may be reduced using this method. The cylinder-based formulation elicits similar mortality levels against stored product insects as the traditional pellet formulation, but utilizes only about half as much active ingredient (Phillips *et al*. 1996, Noyes, *et al*. 1997). Also, this formulation may be used with re-circulation in sealed bins and can be controlled by electronic monitoring of gas concentrations (Chakrabarti 1997, Noyes, *et al*. 1997, Bell *et al*. 1997b). Phosphine supplied from ECO_2Fume was found to be equally effective to MB for the control of rice weevil, *S. oryzae,* in bagged wheat treated in storage sheds in Syria (Wontner-Smith *et al*. 2001). For this method to be effective suitable infrastructure and properly trained technicians must be available. Cylinder-based formulations of phosphine are available commercially in only a few countries. Marketing strategies and cost may limit widespread adoption of this formulation.

Guidelines for the use of phosphine include:

- the commodity temperature should be more than 15°C for most commodity treatments but certain pests are susceptible to phosphine down to 5°C with long exposures;
- the exposure period often needs to be prolonged for effective action against all developmental stages of pests, typically 5 to 15 days, depending on the method of distributing the phosphine, the temperature and the target species;
- proven and well controlled techniques must be used to avoid the development of resistance;
- for aluminium phosphide formulations, the equilibrium relative humidity produced by the commodity should be more than 30% to ensure full evolution of phosphine from the formulation within the exposure period.

Phosphine is routinely used to control insects in a wide range of commodities in storage and further research is only needed to modify commercial practices. The toxicity of phosphine to many arthropod pests is well researched and dosage schedules are available for the common stored product insects and mites (Annex 5.4).

The period of exposure has a much more important role than concentration levels in the toxicity of phosphine. The use of *ct*-products as a measure of dosage for phosphine is not valid unless the exposure period over which it applies is stated. All stages in the life cycle of stored-product insects have a broadly similar tolerance to methyl bromide (a factor of 3x or so). However, there is a high degree of variation in tolerance to phosphine, with eggs and pupae being much more tolerant than larvae and adults. Mites are difficult to control with phosphine since the egg stage is highly tolerant, but a recent study showed that dosages in excess of 150 g h m^{-3} over a six-day exposure at 10^{o}C killed all eggs of *Acarus siro* (Wilkin *et al*. 1999). A recent review of data on time/dose mortality of phosphine to insects has been given by Annis (2001).

5.5.22.1 Resistance to phosphine

High levels of resistance have been observed, particularly in tropical areas, following frequent use of the fumigant in conditions of poor gastightness (Taylor 1989, Price and Mills 1988). There have been numerous control failures attributable to this resistance. Insect populations are capable of developing resistance to phosphine relatively easily. It is important to use correct exposure and application technology to avoid development of resistance and thus loss of this useful alternative. Short fumigation periods (i.e. less than 3 days), employing low concentrations of phosphine, provide the conditions in which insect resistance can develop. Repeated use of phosphine fumigation in flour mills in Hawaii has already led to suspected resistance in local flat grain beetle populations (*Cryptolestes* spp.) (Pierce and Sorum 1998).

The considerable body of work on phosphine resistance and mode of action is reviewed by Chaudhry (1997). Reichmuth (1991) has described a quick test for the detection of resistance to phosphine on the base of the observation of the time to full narcosis being less than 30 minutes in susceptible insects. Resistance management is an important consideration when using phosphine. The effect of resistance to phosphine can at present be overcome provided that the gas concentration needed can be maintained for the longer exposure periods required by more tolerant strains. In leaky situations such as silos, insect control may be carried out by a continuous input of fumigant using a phosphine-carbon dioxide mixture from a pressurised cylinder (SIROFLO system, Winks 1990). However, for conventional dosing, the degree of gastightness of the enclosure should be improved as far as possible, e.g. as described for enclosures around stacks of bagged grain in Anon. (1989) and MacDonald and Reichmuth (1996), so that gas may be retained for a sufficient period. Multiple dosing may also assist. The need to combat the emergence of insect resistance to phosphine in Australia has been indicated by Collins (2000).

5.5.22.2 Phosphine use on grain in store and in transit

Phosphine is widely used for treating infestation in bulk and bagged grain and grain products in many countries. Typically, aluminium phosphide preparations are added to the grain, or placed on the grain surface or near the product to be fumigated within the fumigation enclosure. These release phosphine over a period of hours or days on contact with ambient moisture vapour. This process has superseded use of methyl bromide in most parts of the world. However, methyl bromide is still sometimes used, particularly at point of import or export (e.g. into Japan) or on stacks of bagged grain (e.g. parts of Africa, Singapore). In these cases the speed of action and recognised effectiveness against pests of quarantine significance makes methyl bromide the preferred, and, in many cases, the only currently approved alternative to fumigation with phosphine. Discussion of recent advances in phosphine treatment of grain against infestation can be found particularly in Navarro and Donahaye (1993), Highley *et al.* (1994) and Donahaye *et al*. (1997).

Where regulations permit, in-transit fumigation of bulk and bagged grain on board ship can replace disinfestation with methyl bromide at point of export. Shipboard in-transit fumigation with phosphine is now a well-developed technology (Redlinger *et al.* 1979, Leesch *et al.* 1986, Watson *et al*. 1999, 2001). It requires ships of appropriate design and stringent safety precautions (Snelson and Winks 1981, IMO 1996, Watson *et al*. 1999, 2001). Several grain-exporting countries, including Canada and Australia, require grain to be free of infestation at point of export and thus cannot use the system. However, technically, it presents a method where the slow action of phosphine does not interfere substantially with the flow of trade through export ports and thus presents a feasible alternative to rapid methyl bromide treatments ashore.

Phosphine may be suitable as an alternative to methyl bromide for treatment of empty ships and barges for rodent and insect control prior to loading commodity. Some developing countries currently use methyl bromide for this purpose. While phosphine is rapidly lethal to rodents, its slow action against insect pests, and consequent demurrage costs, may limit its usefulness. Where ships contain cargo, in-transit fumigation with phosphine or modified atmosphere treatments may be feasible.

5.5.22.3 Phosphine uses in other situations

Besides its use on grain, phosphine is used to fumigate many other products in warehouses and other situations. In museums it has been used to treat wooden objects, paper and other materials of vegetable origin. With some materials, e.g. furs and paper, phosphine may be preferred over methyl bromide, because of the reduced risk of taint. Because the gas may adversely affect metals (copper, silver, gold) and pigments in paintings it is rarely used for treating objects of this type.

Most pests of dried fruit and nuts are highly susceptible to phosphine and shorter exposure times can be used than with stored grain. In the latter case, longer periods are needed to control *Sitophilus* spp. These do not attack dried fruit or nuts. Walnuts treated with cylinder formulations of phosphine are not tainted, a problem encountered with older formulations. Disinfestation of dried fish using phosphine has been reported by Friendship (1990) and this fumigant would appear to provide effective control of the common insect pests infesting this commodity.

Phosphine is often used to disinfest herbs and spices, particularly where there may be the possibility of excessive residues with methyl bromide. The longer exposure time required for effectiveness of phosphine compared with methyl bromide provides a disincentive to its use when pests are detected on importation in consignments of herbs or spices. There is concern over possible taint with use of phosphine (and methyl bromide).

Phosphine is very widely used for tobacco disinfestation, almost entirely replacing former use of methyl bromide. Pest management programmes generally rely on phosphine coupled with an organised system of monitoring and localised action as necessary (Ryan 1995).The rate of use varies between 1 and 4 g m^{-3} and the duration of treatment from 5 - 7 days (occasionally up to 15 days) according to the temperature (Geneve 1972, Geneve *et al.* 1986) . However, in recent years phosphine resistance in the cigarette beetle *Lasioderma serricorne* has been reported (Rajendran and Narasimhan 1994) and is becoming widespread (Savvidou *et al*. 2002). To combat the increasing threat of resistance, exposure times for treatment will need to be extended from the 5-7 days normally used.

Phosphine can be used to fumigate structures in some situations. It has proved effective against wood-boring insects in Norwegian churches. It provides good penetration into timber and its efficacy against some pests is well researched and understood. There is, however, limited efficacy data for many wood destroying insects and thus there is a need for further research or documentation to determine the feasibility of using this product in dwellings. Phosphine can cause corrosion problems on copper, or gold and silver alloys, particularly under high humidity conditions. This is of particular concern in mills and food processing premises where sensitive control equipment may be affected. Phosphine was used annually in a mill in Mauritius, but this use has been discontinued for this reason. Brigham (1998) described the conditions leading to corrosion as a basis of providing guidelines to limit this problem.

To overcome the disadvantages of using phosphine alone for structural disinfestation, phosphine (0.09 - 0.14 g m^{-3}) combined with heat at 32 - 37°C and carbon dioxide (4 - 6%) is claimed to provide good penetration and a rapid treatment time, similar to that for methyl bromide (Case study 28, McCarthy 1996, Mueller 1996). Registration requirements and additional insurance requirements in some countries will affect commercial uptake. Recent work in Canada has demonstrated the efficacy of this process in Canadian conditions (Anon. 1996). The amount of phosphine used is set at a level to minimise corrosion levels. The risk of selecting insects for phosphine resistance using this method, however, should not be ignored.

MBTOC (1998) gives further detailed discussion of general features of phosphine and its uses.

5.5.23 Spot treatments

Spot treatments are localised measures often applied within food processing facilities such as flour mills or domestic premises when an infestation problem is restricted to a particular location. This may avoid the need to treat the whole structure, thus avoiding fumigation, such as with methyl bromide. Various methods are in use.

5.5.23.1 Spot treatments by electrocution

High voltage electricity, or electrocution, is localized option for controlling drywood termites. The device currently marketed uses high voltage (90,000 volts) but low current (<0.5 amps). Reported efficacy has been mixed and highly dependent on applicator technique (Lewis and Haverty 1996a). The administration of high levels of heat is the probable cause of mortality. For maximum effects, high voltage bursts of electricity are directed at galleries containing termites. Results can be enhanced by drilling holes and inserting metal pins into wood. Success also can vary depending on proximity to certain building materials. The drilling of wall coverings and wood for insertions of metal pins is a destructive treatment technique (Lewis and Haverty 1996a).

5.5.23.2 Spot treatments by liquid nitrogen

Cold can be used as a spot treatment against termites by the injection of liquid nitrogen into confined spaces such as wall voids. It has been used in the U.S. for several years with limited success. It is confined to wall void treatments, not for full sites and is dependent on a thorough inspection of the pest location and the containment area. This technique cannot be used in inaccessible areas. Insulation in walls can affect cold distribution causing warm spots in walls. Interior surfaces can be stained and warping of wooden structural components is possible. Some damage to water pipes has occurred. Deprivation of oxygen has been a concern for workers when leakage occurs. Relative efficacy of localized treatments with liquid nitrogen is highly dosage dependent and varies from ineffective to effective (Lewis and Haverty 1996a). The limitations of this localized treatment include: many locations within structures are not treatable with this method, drilling holes damages wall coverings and wood, large amounts of liquid nitrogen may be needed, and accurately monitoring temperature changes is critical to success (Lewis and Haverty 1996a).

5.5.23.3 Spot treatments by microwaves

Microwave heating has been used as a spot treatment with very limited success. It has primarily been limited to the control of drywood termites. It destroys insects, but can damage wood by scorching it. It has been used in the U.S. for several years with limited efficacy. As a localised treatment, microwave heating success is dependent on a thorough inspection and the evenness of the microwaves to avoid hot and cold spots. There is concern about the health risks because of the difficulty of shielding microwaves. Some damage to properties has occurred because of overheating of the target area. Further research is needed before this technique is recommended and it may be only applicable to accessible wood.

5.5.24 Sulphuryl fluoride

Sulphuryl fluoride was developed in the late 1950's in the USA as a structural fumigant, mainly for termite control. Sulphuryl fluoride (SF) has been marketed since 1961 under the trade name Vikane for structural fumigation. The compound is now being developed as a practical alternative to methyl bromide for many uses, including durable products and mills under the trade name ‘ProFume’ (Welker *et al*., 2000). The fumigant has also been manufactured and marketed in China under the trade name “Xunmiejin” since 1983, being used mostly on artefacts, timber or wood products, and for treatment of export containers.

Sulphuryl fluoride (SO_2F_2) is a non-flammable, odourless and colourless gas. The boiling point of SF is -55.2°C. Because of the low boiling point and high vapour pressure, SF readily vaporizes under normal fumigation conditions, thus allowing rapid dispersion after introduction. Sulphuryl fluoride is generally non-corrosive, an important characteristic for a fumigant, especially in settings where sensitive equipment and electronic devices are present. It may generate corrosive hydrofluoric acid under damp conditions. Recent studies have show that after successive fumigations giving a combined *ct*-product of 22,000 g h m^{-3} computer equipment continued to operate normally (Bell *et al*. 2002b).

Sulphuryl fluoride has very low reactivity as a gas, an important factor for treatment of museum artefacts and mills. However, it will react to form corrosive hydrogen fluoride at temperatures exceeding 400° C. This acid can etch metals, glass or other surfaces near the heat source. Thus, prior to a fumigation, all open flames and glowing heat filaments are turned off or disconnected.

Sulphuryl fluoride has many advantages as a fumigant:

- It rapidly penetrates porous materials;
- It has low sorption on fumigated materials;
- It rapidly aerates from materials and commodities;
- It does not react with materials to form unpleasant odours.

Sulphuryl fluoride is toxic to post-embryonic stages of insects (Kenaga 1957, Bond and Monro 1961, Reichmuth *et al*. 1996), but the eggs of many species, including cockroaches, moths and beetles are very tolerant, especially at lower temperatures, requiring concentrations of up to 50 g m^{-3} and exposures of up to three days for complete kill (Bell *et al*. 1999). Eggs of *Ephestia kuehniella* at 25^{o}C required a *ct*-product of about 1000 g h m^{-3} to prevent hatch and 800 g h m^{-3} to prevent emergence (Williams and Sprenkel 1990, Bell and Savvidou 1999). Research has indicated that the lower activity on eggs is primarily due to slow penetration through the eggshell (Outram 1967). Effective dosages for all life stages can be obtained by varying concentration and exposure time.

At the present time, SF is only registered or licensed for use as a structural fumigant in a limited number of countries, including the United States, China, Germany, Japan, Sweden and the Caribbean. Sulphuryl fluoride is a direct replacement for methyl bromide for drywood termite control and in the USA (California) this substitution has led to almost complete replacement of methyl bromide for this use. In the USA, it is registered for use to control a wide range of other pests including Formosan subterranean termites, longhorn beetles, powderpost beetles, furniture and carpet beetles, clothes moths, cockroaches, and rodents infesting buildings, furnishings, construction materials and transport vehicles (not including submarines and aircraft).

In 1994 SF was licensed for use as a structural fumigant in Germany with an estimated 50 historic buildings (primarily churches) being treated per year. In 1995, a similar registration was granted in Sweden.

Research is in progress to support food tolerances in the United States and maximum residue levels in the European Union for sulphuryl fluoride and to determine optimal application recommendations. This research may enable sulphuryl fluoride to be used in postharvest markets prior to methyl bromide phase-out.

An experimental fumigation was undertaken in a semolina mill in Italy in July 2001 (Drinkall *et al*. 2002) to validate the activity of sulphuryl fluoride determined from laboratory chamber fumigations. Complete kill was obtained in bioassays containing a wide range of stored product pests included in the treatment. Three additional trials were undertaken in association with the Federal Biological Research Centre for Agriculture and Forestry, Institute of Stored Product Protection, Berlin (Froba *et al*. 2002). They were designed to validate that effective control of common flour mill pests, recorded in chamber fumigations, could be achieved under field conditions. In the three field trials the temperature was raised by the use of either coil in oil electric heaters placed in the mill or external oil burners creating hot air ducted into the structure. Following exposures that ranged from 30 to 48 hours, and aeration, the bioassays were removed and insect mortality determined. In all three trials a high level of control was achieved for all stored product pest of all life stages.

Efficacy research is underway both in the laboratory and in the field to define dosages and treatment practices to optimise the control of key postharvest insect pests, including their egg stages. A guide, the "Fumiguide", has been produced for SF that sets out dosages for application under a range of conditions (Schneider *et al*. 2002). Laboratory efficacy studies being conducted by the USDA-ARS in Fresno, California; Central Science Laboratory in the UK; and Federal Biological Research Centre for Agriculture and Forestry in Germany, to define the dosages required to control all the life stages of target pests.

The laboratory findings are being validated by fumigations of multiple wheat and rice mills within the United States and Europe. These field trials have been designed to further refine fumigant dosages for precision fumigation practices. This research will lead to enhanced sealing techniques, gas confinement, half loss time, fumigant introduction, monitoring and aeration practices (Williams *et al*. 2001).

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Food quality studies are being conducted on a variety of dried fruits and tree nuts in cooperation with the California Dried Fruit and Tree Nut Association and other commodity groups. SF can offer a rapid treatment for walnuts under vacuum a direct replacement for methyl bromide (Zettler and Leesch 2000). Similar studies on cereal grains, including examinations of baking quality, taste and other quality measures are in progress. Protocols have been developed to meet the requirements of the food production industry in the United States and Europe. Food residue studies have been completed for cereal grains, dried fruit, and tree nuts.

Registration of sulphuryl fluoride by Dow AgroSciences, producer of ProFume, is being actively pursued for dried fruit, nuts and cereal grains in USA. Approval in Europe for use in mills is projected for 2004.

5.5.25 Vacuum systems

The use of vacuum as a control measure for pests of durable products has recently received new impetus with the development of flexible enclosures of sufficient quality to hold low pressures for extended periods, removing the former dependency on expensive steel vacuum fumigation chamber facilities. The use of vacuum may also improve the efficacy of other control agents, particularly fumigants. Some effects of temperature and humidity on the tolerance of storage pests to vacuum have recently been described (Mbata and Phillips 2001).

Field trials in a demonstration project in Turkey found that low pressure (25-30 mm Hg abs.) created by a small vacuum pump attached to a sealed flexible (PVC) enclosure provided complete mortality of mixed stages of *E. cautella* and *T. castaneum* in 3 days (Navarro *et al.* 2001, Finkelman *et al.* 2002). A similar vacuum-hermetic system provided effective disinfestation of cocoa beans in trials in the Ivory Coast (Case study 23). The efficacy against a wider range of pests normally associated with cocoa beans and other commodities remains to be determined. Complete mortality of test insects was observed after 3 days. When compared to methyl bromide this treatment method requires a longer exposure period. Researchers reported that the system was economically viable, and safer for operators than MB fumigation (Navarro and Donahaye 2000, Navarro *et al*. 2001, 2002, Villers 2002).

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Annex 5.1 Pest organisms in durables, sometimes treated with MB, including wood and processed timber, listed by infested commodity

Infested Product [a]	Pest Organism/ Latin Name	Pest Organism/ Common Name
D	*Anthrenus* spp.	Carpet beetles
D	*Attagenus pellio*	Museum beetle
D	*Dermestes lardarius*	Larder beetle
D	*Dermestes maculatus*	Hide beetle
D	*Necrobia ruficollis*	Red-necked bacon beetle
D	*Necrobia rufipes*	Copra beetle
D	*Trogoderma* spp.	Warehouse beetles
D	*Tyrophagus* spp.	Cheese and bacon mites
F	*Alphitobius laevigatus*	Black fungus beetle
F	*Amyelois transitella*	Navel orange worm
F	*Anarsia lineatella*	Peach twig borer
F	*Cadra figulilella*	Raisin moth
F	*Carpoglyphus lactis*	Dried fruit mite
F	*Carpophilus dimidiatus*	Dried fruit beetle
F	*Carpophilus* spp.	Dried fruit beetles
F	*Cydia pomonella*	Codling moth
F	Dermaptera	Earwigs
F	*Drosophila* spp.	Vinegar flies
F	*Ectomyelois ceratoniae*	Carob moth
F	*Ephestia cautella*	Almond (Tropical, warehouse) moth
F	*Ephestia elutella*	Warehouse (cocoa, tobacco) moth
F	*Forficula auricularia*	Common earwig
F	Formicidae	Ants
F	*Lasioderma serricorne*	Cigarette beetle
F	*Oryzaephilus mercator*	Merchant grain beetle
F	*Oryzaephilus surinamensis*	Saw-toothed grain beetle
F	*Plodia interpunctella*	Indian meal moth
F	*Typhaea stercorea*	Hairy fungus beetle
F	*Vitula edmandsae serratilinella*	Dried fruit moth
G	*Acarus siro*	Flour mite
G	*Acarus siro*	Flour mite
G	*Ahasverus advena*	Foreign grain beetle
G	*Cernuella* spp.	Snail
G	*Cochlicella* spp.	Snail
G	*Corcyra cephalonica*	Rice moth
G	*Cryptolestes ferrugineus*	Rust-red grain beetle, rust red flour
G	*Cryptolestes pusillus*	Flat grain beetle
G	*Cryptolestes turcicus*	Flat grain beetle
G	*Ephestia cautella*	Almond (Tropical, warehouse) moth
G	*Ephestia elutella*	Warehouse (cocoa, tobacco) moth
G	*Ephestia kuehniella*	Mediterranean flour moth
G	*Gnatocerus cornutus*	Broad horned flour beetle

G	*Liposcelis bostrichophila*	Book louse
G	*Liposcelis* spp.	Booklice, psocids
G	*Nemapogon granellus*	European grain moth
G	*Niptus hololeucus*	Golden spider beetle
G	*Oryzaephilus mercator*	Merchant grain beetle
G	*Oryzaephilus surinamensis*	Saw-toothed grain beetle
G	*Plodia interpunctella*	Indian meal moth
G	*Prostephanus truncatus*	Larger grain borer
G	*Ptinus fur*	White-marked spider beetle
G	*Ptinus* spp.	Spider beetles
G	*Ptinus tectus*	Australian spider beetle
G	*Rhyzopertha dominica*	Lesser grain borer
G	*Sitophilus granarius*	Granary weevil
G	*Sitophilus oryzae*	Rice weevil
G	*Sitophilus zeamais*	Maize weevil
G	*Sitotroga cerealella*	Angoumois grain moth
G	*Stegobium paniceum*	Drugstore beetle
G	*Tenebrio molitor*	Yellow mealworm
G	*Tenebroides mauretanicus*	Cadelle
G	*Tribolium castaneum*	Rust red flour beetle
G	*Tribolium confusum*	Confused flour beetle
G	*Trogoderma granarium*	Khapra beetle
G	*Trogoderma* spp.	Warehouse beetles
G	*Typhaea stercorea*	Hairy fungus beetle
L	*Acanthoscelides obtectus*	Dried bean beetle
L	*Callosobruchus chinensis*	Cowpea beetle
L	*Callosobruchus maculatus*	Cowpea beetle
L	*Caryedon serratus*	Groundnut borer
L	*Zabrotes subfasciatus*	Mexican bean beetle
M	*Cryptolestes ferrugineus*	Rust-red grain beetle, rust red flour
M	*Cryptolestes pusillus*	Flat grain beetle
M	*Ephestia kuehniella*	Mediterranean flour moth
M	*Lasioderma serricorne*	Cigarette beetle
M	*Stegobium paniceum*	Drugstore beetle
M	*Tribolium castaneum*	Rust red flour beetle
M	*Trogoderma granarium*	Khapra beetle
M	*Trogoderma* spp.	Warehouse beetles
N	*Alphitobius laevigatus*	Black fungus beetle
N	*Amyelois transitella*	Navel orange worm
N	*Anarsia lineatella*	Peach twig borer
N	*Araecerus fasciculatus*	Coffee bean weevil
N	*Cadra figulilella*	Raisin moth
N	*Carpophilus* spp.	Dried fruit beetles
N	*Corcyra cephalonica*	Rice moth
N	*Cryptolestes ferrugineus*	Rust-red grain beetle, rust red flour
N	*Cryptolestes pusillus*	Flat grain beetle

N	*Curculio carvae*	Pecan weevil
N	*Curculio nasicus*	Curculio
N	*Cydia caryana*	Hickory shuckworm
N	*Cydia pomonella*	Codling moth
N	*Dermestes* spp.	Hide beetles
N	*Ephestia cautella*	Almond (Tropical, warehouse) moth
N	*Ephestia elutella*	Warehouse (cocoa, tobacco) moth
N	*Ephestia kuehniella*	Mediterranean flour moth
N	Formicidae	Ants
N	*Hypothenemus hampei*	Coffee berry borer
N	*Lasioderma serricorne*	Cigarette beetle
N	*Oryzaephilus mercator*	Merchant grain beetle
N	*Oryzaephilus surinamensis*	Saw-toothed grain beetle
N	*Plodia interpunctella*	Indian meal moth
N	*Tribolium castaneum*	Rust red flour beetle
N	*Tribolium confusum*	Confused flour beetle
N	*Trogoderma granarium*	Khapra beetle
N	*Trogoderma* spp.	Warehouse beetles
O	*Tribolium castaneum*	Rust red flour beetle
O	*Tyrophagus* spp.	Cheese and bacon mites
T	*Ephestia elutella*	Warehouse (cocoa, tobacco) moth
T	*Lasioderma serricorne*	Cigarette beetle
W	*Anobium punctatum*	Furniture beetle
W	*Attagenus* spp.	Carpet beetle
W	*Ctenolepsima villosa*	Oriental silverfish
W	*Dermestes lardarius*	Larder beetle
W	*Dermestes maculatus*	Hide beetle
W	*Dermestes* spp.	Hide beetles
W	*Dinoderus minutes*	Smaller bamboo shot hole borer
W	*Gastrallus immarginatus*	Book borer
W	*Hylotrupes bajulus*	House longhorn beetle
W	*Lepisma saccarina*	Silverfish
W	*Liposcelis bostrichophila*	Book louse
W	*Liposcelis* spp.	Booklice, psocids
W	*Lyctus* spp.	Powder-post beetles
W	*Tinea* spp.	Clothes moths
W	*Tineola bisselliella*	Clothes moth

[a] D: dried meat, dried fish, pet food, F: dried fruits, G: grain, cereals and products, L: grain legumes, M: medicinals, spices, seasonings, drugs, N: nuts, cocoa, coffee, O: oilseeds, S: seeds for planting, T: tobacco, W: wood, wood products, logs, timber, artefacts, wool

Annex 5.2 Estimates of the minimum *ct*-product (g h m^{-3}) of methyl bromide for a 99.9 per cent kill of various stages of a number of insect species at 10, 15, 25 and 30^{o}C and 70 per cent RH. (Heseltine and Thompson 1974)

		Temperature (^{o}C)			
Species	**Stage**	10	15	25	30
Callosobruchus chinensis	Pre-adult stages	175	85	40	-
Cryptolestes minutus	Cocoons	170	145	125	-
Ephestia cautella	Pupae	-	70	55	-
Ephestia elutella	Diapausing larvae	360	360	205	180
Ephestia kuehniella	Pupae	-	75	60	-
Lasioderma serricorne	Cocoons	-	180	100	-
Oryzaephilus surinamensis	Adults	85	85	50	40
Plodia interpunctella	Diapausing larvae	300	250	105	-
Ptinus tectus	Cocoons	170	155	100	-
Ptinus tectus	Adults	155	125	85	-
Rhyzopertha dominica	Early pre-adult stages	-	40	40	-
Rhyzopertha dominica	Later pre-adult stages	-	75	45	-
Rhyzopertha dominica	Adults	80	65	40	-
Sitophilus granarius	Early pre-adult stages	115	75	50	50
Sitophilus granarius	Later pre-adult stages	200	115	65	65
Sitophilus granarius	Adults	55	55	35	-
Sitophilus oryzae	Pre-adult stages	-	105	85	-
Sitophilus oryzae	Adults	50	30	30	15
Tribolium castaneum	Pupae	-	-	125	100

Tribolium castaneum	Adults	125	80	60	50
Tribolium confusum	Pupae	230	180	90	-
Tribolium confusum	Adults	115	85	60	45
Trogoderma granarium	Larvae	290	190	110	70

(A dash in the table indicates that no test was carried out).

Annex 5.3 Methyl bromide dosage table. European Plant Protection Organization (1993a)

Group	Commodities	Dosage (g m^{-3})			Exposure period (h)
		<10ºC	10-20ºC	>20ºC	
1.	Rice, peas, beans, cocoa beans, dried vine fruits	25	15	10	24
2.	Wheat, barley, oats, maize, lentils	50	35	25	24
3.	Pollards, rice bran	70	45	30	48
4a	Sorghum, nuts, figs	75	50	35	24
4b	Groundnuts, oilseeds, dates, empty sacks	75	50	35	48
5.	Oilseed cakes and meals	120	85	60	48
6.	Fishmeal, dried blood etc.	140	100	65	48
7.	Flour	50	50	40	48

Notes:

1. These dosage rates apply to fumigations under gas-proof sheets and in freight containers which are usually fully loaded. If this method is to be used for mites, dosage rates should accordingly be doubled.
2. Penetration of methyl bromide into commodities in Groups 5 and 6 is poor and fumigation may be uneconomic using the recommended dosage rates. In such cases the use of phosphine should be considered and this is the preferred fumigant for Group 7 (flour).
3. To reduce the possibility of taint, the dose for flour should never exceed 50 g m^{-3}.
4. Diapausing larvae of *Trogoderma granarium* (khapra beetle) and *Ephestia elutella* (warehouse moth) are highly tolerant of methyl bromide. In this case, these dosages should be increased by one half and, where applicable, exposure periods increased to 48 h in order to achieve the requisite *ct*-products.

Annex 5.4 Minimum exposure periods (days) required for control of all stages of the stored product pests listed, based on a phosphine concentration of 1.0 g m^{-3}. This dosage is as recommended for good conditions and the dosage applied will usually need to be increased considerably in leaky situations (EPPO 1993b).

		Temperature	
Species	**Common names**	**10 - 20ºC**	**20 - 30ºC***
Oryzaephilus surinamensis	Saw-toothed grain beetle	3	3
Cryptolestes pusillus	Flat grain beetle	5	4
Oryzaephilus mercator	Merchant grain beetle		
Tribolium castaneum	Rust-red flour beetle		
Lasioderma serricorne	Cigarette beetle	5	5
Acanthoscelides obtectus	Dried bean beetle	8	5
Corcyra cephalonica	Rice moth		
Cryptolestes ferrugineus	Rust-red grain beetle		
Plodia interpunctella	Indianmeal moth		
Ptinus tectus	Australian spider beetle		
Rhyzopertha dominica	Lesser grain borer		
Sitotroga cerealella	Angoumois grain moth		
Tribolium confusum	Confused flour beetle		
Ephestia cautella	Tropical warehouse moth	10	5
Ephestia elutella	Warehouse moth		
Ephestia kuehniella	Mediterranean flour moth		

Caryedon serratus	Groundnut borer	10	8
Sitophilus granarius	Grain/granary weevil	16	8
Sitophilus oryzae	Rice weevil		
Sitophilus zeamais	Maize weevil		
Trogoderma granarium	Khapra beetle		

Notes:

* All species listed succumb to a 4-day exposure at this dosage level at 30^oC or above.

For certain commodities in long-term storage where it is necessary to control a mite infestation, two fumigations may be carried out separately by an interval dependent on ambient temperature, allowing eggs surviving the first fumigation to hatch. This interval varies from 2 weeks at 20^oC to 6 weeks at 10^oC (Bowley and Bell 1981).

Chapter

6

Alternatives evaluated in Article 5(1) countries – Response to Decision IX/5(1e)

6.1 Introduction

Under Decision IX/5, agreed at the Ninth Meeting of the Parties to the Montreal Protocol in 1997, the Parties decided *inter alia* that further specific interim reductions on methyl bromide for the period beyond 2005 for Article 5(1) Parties would be decided at the Meeting of the Parties in 2003. This chapter aims to provide Parties with relevant information in response to paragraph 1(e) of Decision IX/5. The full Decision, entitled *Conditions for control measures on Annex E substance in Article 5(1) Parties*, reads as follows:

1. That, in the fulfilment of the control schedule set out in paragraph 8 ter (d) of Article 5(1) of the Protocol, the following conditions shall be met:

(a) The Multilateral Fund shall meet, on a grant basis, all agreed incremental costs of Parties operating under paragraph 1 of Article 5(1) to enable their compliance with the control measures on methyl bromide. All methyl bromide projects will be eligible for funding irrespective of their relative cost-effectiveness. The Executive Committee of the Multilateral Fund should develop and apply specific criteria for methyl bromide projects in order to decide which projects to fund first and to ensure that all Parties operating under paragraph 1 of Article 5(1) are able to meet their obligations regarding methyl bromide;

(b) While noting that the overall level of resources available to the Multilateral Fund during the 1997-1999 triennium is limited to the amounts agreed at the Eighth Meeting of the Parties, immediate priority shall be given to the use of resources of the Multilateral Fund for the purposes of identifying, evaluating, adapting and demonstrating methyl bromide alternatives and substitutes in Parties operating under paragraph 1 of Article 5(1). In addition to the US$ 10 million agreed upon at the Eighth Meeting of the Parties, a sum of US$ 25 million per year should be made available for these activities in both 1998 and 1999 to facilitate the earliest possible action towards enabling compliance with the agreed control measures on methyl bromide;

(c) Future replenishment of the Multilateral Fund should take into account the requirement to provide new and additional adequate financial and technical assistance to enable Parties operating under paragraph 1 of Article 5(1) to comply with the agreed control measures on methyl bromide;

(d) The alternatives, substitutes and related technologies necessary to enable compliance with the agreed control measures on methyl bromide must be expeditiously transferred to Parties operating under paragraph 1 of Article 5(1) under fair and most favourable conditions in line with Article 10A of the Protocol. The Executive Committee should consider ways to enable and promote information exchange on methyl bromide alternatives among Parties operating under paragraph 1 of Article 5(1) and from Parties not operating under paragraph 1 of Article 5(1) to Parties operating under that paragraph;

(e) In light of the assessment by the Technology and Economic Assessment Panel in 2002 and bearing in mind the conditions set out in paragraph 2 of Decision VII/8 of the Seventh Meeting of the Parties, paragraph 8 of Article 5(1) of the Protocol, sub-paragraphs (a) to (d) above and the functioning of the Financial Mechanism as it relates to methyl bromide issues, the Meeting of the Parties shall decide in 2003 on further specific interim reductions on methyl bromide for the period beyond 2005 applicable to Parties operating under paragraph 1 of Article 5(1).

2.That the Executive Committee should, during 1998 and 1999, consider and, within the limits of available funding, approve sufficient financial resources for methyl bromide projects submitted by Parties operating under paragraph 1 of Article 5(1) in order to assist them to fulfil their obligations in advance of the agreed phase-out schedule.

Paragraph 1(e) above refers to paragraph 2 of Decision VII/8, which states:

That, in considering the viability of possible substitutes and alternatives to methyl bromide, the Technology and Economic Assessment Panel shall examine and be guided by the extent to which technologies and chemicals identified as alternatives and/or substitutes have been tested under full laboratory and field conditions, including field tests in Article 5(1) countries and have been fully assessed, inter alia, as to their efficacy, ease of application, relevance to climatic conditions, soils and cropping patterns, commercial availability, economic viability and efficacy with respect to target pests.

Controls on MB that currently apply to Article 5(1) countries under Article 2H consist of: a freeze on production and consumption from 1 January 2002 based on the average production and consumption in the years 1995-1998; 20% reduction from 1 January 2005 and 100% reduction by 1 January 2015. This excludes the volumes of methyl bromide produced/consumed for quarantine and pre-shipment applications (Ozone Secretariat 2000). Individual Article 5(1) countries become subject to these controls when they have ratified the Copenhagen Amendment of the Montreal Protocol, an amendment that added MB and HCFCs to the list of controlled ozone-depleting substances in 1992. By October 2002, 102 Article 5(1) countries had ratified the Copenhagen Amendment at national level. This covers almost all countries that use MB. China and India, however, have not ratified the Amendment and are both MB producers and consumers. The Chinese government has officially informed the Ozone Secretariat that they intend to ratify (Zhang 2002).

TEAP requested MBTOC to provide information relating to Decision IX/5(1e), including the extent to which alternatives have been tested in Article 5(1) countries, the progress made by demonstration projects in evaluating efficacy with respect to target pests, and ease of application, availability, relevance to climatic conditions, soils and cropping patterns found in Article 5(1) regions. This chapter also identifies the alternatives that Article 5(1) countries have selected for wide scale national adoption as part of MB phaseout projects and progress in MB reductions in Article 5(1) regions It focuses on the demonstrated alternatives in Article 5(1) countries, and examines *inter alia* the extent to which these alternatives have been tested and their commercial availability. Much of the information in this chapter is drawn from the projects of the Montreal Protocol's Multilateral Fund (MLF), which were developed in response to Decision IX/5. Technical descriptions or other background information about alternative technologies are not given here: such information is provided in Chapters 4 (alternatives for soil treatments) and 5 (alternatives for commodity and structural treatments).

6.2 Projects on MB Alternatives

The Multilateral Fund provides developing countries with financial and technical assistance to address the phaseout of ozone depleting substances. By December 2002, the MLF had approved a total of 232 MB projects in more than 63 Article 5(1) countries, with expenditure of more than US $50 million. This includes all types of MB-related activities: demonstrations, technical assistance, project preparation, training, workshops, awareness raising and, more recently, MB phaseout projects (which are mainly classified as 'investment projects'). The MLF projects can be classified into the following broad categories:

- 44 demonstration projects, 2 of which were cancelled, giving a net total of 42. Of these, 8 were 'bilateral' projects, implemented by Australia, Germany or Canada. For detailed information refer to Section 6.4 and list of projects in Table 6.3.

- 52 information and awareness-raising activities, including workshops, technical assistance, and information exchange on MB phaseout and alternatives, policy development and various other activities.

- 98 for the preparation of new projects, including collection of data on MB uses; and

- 38 phaseout projects, some of which include demonstration stages. Approximately 4 projects are implemented by bilateral agencies. Lists of projects are given in Tables 6.7 and 6.8.

In addition, a number of MB demonstration projects have been funded from sources other than the MLF, by Article 5(1) countries themselves - for example China – or bilateral assistance from the governments of Australia, Germany (GTZ), Italy, Canada and the Global Environment Facility (GEF). In some countries farmers or exporters associations have also financed experiments to identify alternatives to MB; examples include those in Morocco, Egypt, Jordan, Lebanon and Kenya.

Table 6.1 MB projects funded by the Multilateral Fund and other bodies

Project type	**Multilateral Fund**	**Other government bodies**	**Total**
Demonstration projects	42 (a)	5	47
MB phaseout projects	38		38
Workshops, technical assistance, awareness raising, project preparation, etc.	52	> 7	> 59
Project preparation	98	1	99
Total	230 (a)	> 13	> 243

(a) Table excludes 2 demonstration projects that were approved but later cancelled.

6.3 MB Production and Consumption in Article 5(1) Countries

This section provides an overview of MB production and consumption in Article 5(1) countries, covering trends in total consumption, regional breakdown, national trends, and the major crops and uses of MB. The use of MB for quarantine and pre-shipment (QPS) is not addressed, because these uses are exempt from control under Article 2H of the Protocol and are therefore not covered by Decision IX/5(1e).

6.3.1 MB production in Article 5(1) countries

MB is at present produced in China, India and Romania. The Democratic People's Republic of Korea reported that their MB production ceased around 1995 (Pak Chun Il 1999). The total Article 5(1) production in 2000 was about 2572 tonnes for controlled uses (excluding QPS and feedstock), based on data from the Ozone Secretariat and national ozone offices. This accounts for less than 6% of global MB fumigant production for controlled MB uses. China is the only Article 5(1) country that produces more than 500 tonnes MB; its MB production rose by more than 700% between 1995 and 1998. However, China's MB production for controlled uses increased only slightly between 1998 and 2000.

6.3.2 Total Article 5(1) consumption

Table 2 presents estimates of Article 5(1) MB consumption from 1991 to 2000, excluding QPS, based primarily on the data reported up to November 2002 to the Ozone Secretariat by the Parties under Article 7 of the Protocol. Gaps in the data set were filled by using data from previous years. The estimates presented in Table 6.2

are the best available to MBTOC at this time. Some uncertainties in the data arise due to difficulties in reporting and applying the definition of QPS. A number of countries have not yet reported their 2000 national MB consumption to the Ozone Secretariat. For these reasons, actual MB consumption may be somewhat higher than indicated by the figures in Table 6.2.

In 1998 Article 5(1) consumption accounted for about 29% of global consumption; in 2000 it accounted for about 36% of global consumption (excluding QPS in both cases). The change was largely due to the relative decrease in MB consumption in non-Article 5(1) regions.

Historically, MB consumption in Article 5(1) countries more than doubled during the 1990s, increasing from about 8,460 metric tonnes in 1991 to about 17,600 tonnes in 1998, excluding QPS (Table 6.2). This represented an annual increase of about 15% per year on average. However, since 1998 the total Article 5(1) consumption trend has changed significantly; MB consumption decreased at approximately 3% per year on average between 1998 and 2000. Estimates for 2000 indicate that Article 5(1) MB consumption was reduced to approx. 16,440 tonnes. This figure is preliminary, but all data sources indicate that total Article 5(1) MB consumption was reduced between 1998 and 2000. National MB consumption fell by more than 20% in some Article 5(1) countries.

The MB reductions have been achieved as a result of:

a) The implementation of country-driven demonstration projects that have been funded by the MLF to identify, validate and adapt alternatives to MB (see Section 6.4);

b) Information exchange and training programs on available and locally validated alternatives (see Section 6.4.3);

c) Implementation of MB phaseout projects in Article 5(1) countries (see Section 6.5) and

d) Consumer concerns and market pressure to adopt production practices that restrict the use of MB and other chemicals that have substantial environmental impacts (see Section 3.6.3).

6.3.3 Consumption by region

Estimates of MB consumption by region (Table 6.2, Figure 6.1) indicate that MB consumption is greatest in Latin America and the Caribbean (37%), followed by Africa (26%), South and Southeast Asia and the Pacific (26%), West Asia (also referred to as the Middle East) (6%) and CEIT/Europe (5%). These regions correspond to the regions used in UNEP's ozone networks. Use of MB in Latin America/Caribbean was reduced from about 7030 tonnes in 1998 to about 6120 tonnes in 2000. Consumption in Africa was reduced from about 5160 tonnes in 1998 to about 4460 tonnes in 2000. However, in the same period, MB in the South/Southeast Asia and Pacific region increased from about 3700 to about 4270 tonnes, while in West Asia MB consumption increased from about 720 tonnes in 1998 to about 860 tonnes in 2000 (based on data available in October 2002).

6.3.4 National consumption trends

Analysis of methyl bromide consumption in 120 Article 5(1) countries showed the following diverse consumption patterns in 2000 or latest year recorded by the Ozone Secretariat (excluding QPS) (Figure 6.2):

- 52 (43%) countries have zero MB consumption or no reported MB consumption
- 42 (35%) consumed less than 50 tonnes MB
- 0 (0%) consumed 50 - 99 tonnes MB
- 8 (7%) consumed 100 - 199 tonnes MB
- 6 (5%) consumed 200 - 499 tonnes MB
- 12 (10%) consumed > 500 tonnes MB

Figure 6.1. Relative consumption of MB (by region) in Article 5(1) countries

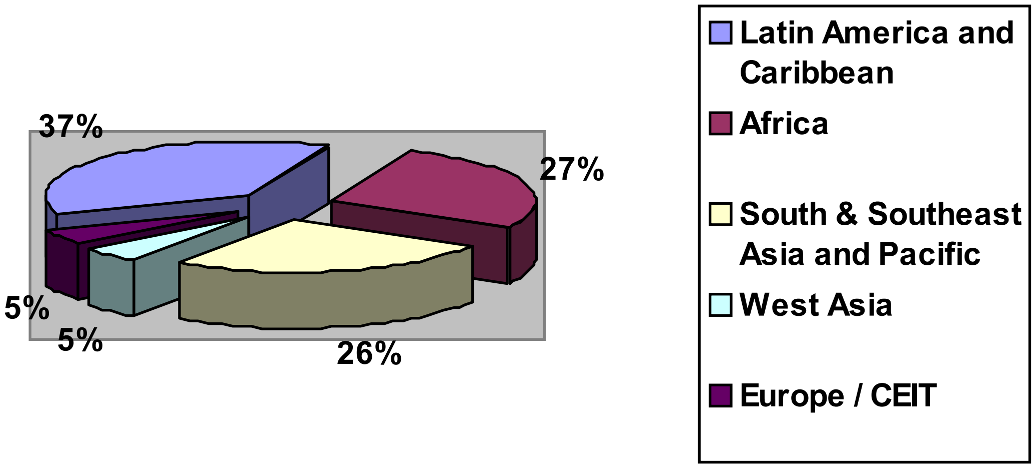
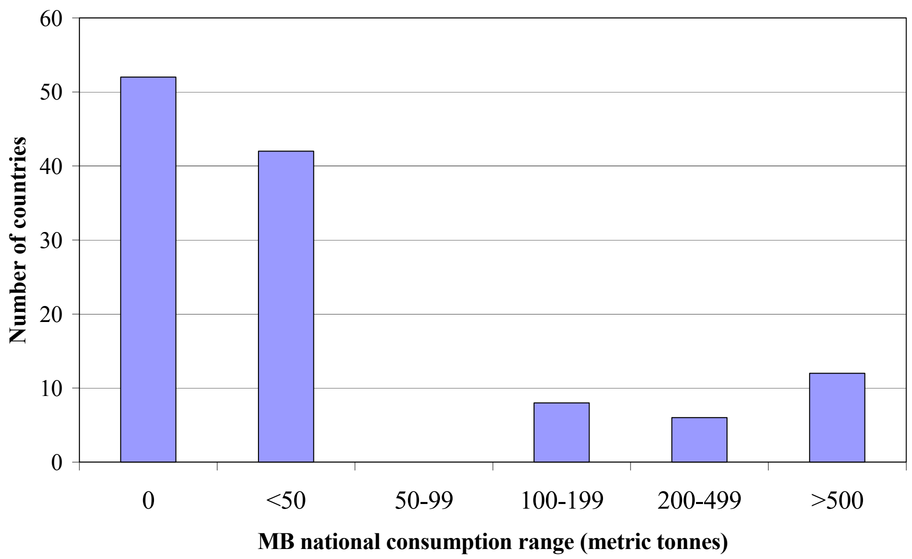


Table 6.2 Reported consumption of MB in Article 5(1) regions (excluding QPS and feedstock) in metric tonnes

A5 regions	1991	1995	1996	1997	1998	2000 estimate
Latin America & Caribbean	2,626	6,159	5,870	6,502	7,031	6,117 (37%)
Africa	3,009	4,404	3,854	4,010	5,162	4,456 (27%)
South/Southeast Asia & Pacific	1,787	1,809	2,236	3,023	3,700	4,269 (26%)
West Asia	244	870	1,177	1,058	717	863 (5%)
CEIT, Europe	794	1,250	1,409	1,083	985	734 (5%)
Total	**8,460**	**14,493**	**14,546**	**15,675**	**17,595**	**16,438** (100%)

Source of data for 1991-2000: Ozone Secretariat data (reported by Parties under Article 7 of the Montreal Protocol by October 2002). Where 2000 data was not available, it was assumed that the consumption was unchanged from 1999.

Figure 6.2 Distribution of MB consumption by Article 5(1) countries in 2000



The following countries consumed more than 500 tonnes MB in 2000 (in order of consumption, excluding QPS): China, Morocco, Mexico, South Africa, Guatemala, Argentina, Brazil, Egypt, Costa Rica, Honduras, Zimbabwe and Turkey.

China's MB consumption increased steadily from the mid-1990s, when MB canisters became available for soil use, reaching 3267 tonnes (excluding QPS) in 1998. It declined slightly to 2664 tonnes in 1999, and then increased to 3501 tonnes in 2000 (based on data from Ozone Secretariat and SEPA). MB consumption in Morocco increased steadily from 221 tonnes in 1991 to a peak of 1599 tonnes in 1998. Consumption was reduced to 1450 tonnes in 2000. Both China and Morocco plan to implement MB phaseout projects that will reduce MB consumption in the coming years. Mexico's consumption reached its peak of 5421 tonnes in 1994, fluctuated during the late 1990s (average 1635 tonnes) and then fell to 1445 tonnes in 2000, according to data from the Ozone Secretariat and the national ozone unit of Mexico.

Although many individual Article 5(1) countries increased their MB consumption substantially during the mid 1990s, analysis of the recent Ozone Secretariat data also shows that, in the period since 1998, the reported MB consumption (1998-2000, excluding QPS) decreased by more than 20% in some countries, such as Algeria, Brazil, Cuba, Iran, Jamaica, Jordan, Kenya, Madagascar, Mexico, Moldova, Paraguay, Romania, Senegal, Venezuela and Zimbabwe. A proportion of these MB reductions has been achieved as a result of MB projects and related activities, for example in Brazil, China, Cuba and Jordan (Section 6.5). Other factors included demonstration projects, information exchange, training, market pressures and activities of individual governments and MB users

6.3.5 Major uses of MB in Article 5(1) countries

MBTOC carried out a survey of ozone offices and experts in Article 5(1) countries from November 2001 to March 2002, to provide up-dated estimates of the breakdown of MB uses. The survey focused primarily on countries that consume more than 100 tonnes MB, but some smaller countries were included in cases where data was readily available. Based on the results of MBTOC's survey and Ozone Secretariat data in 2000, Article 5(1) countries were estimated to use approximately 22% (range 19-24%) MB for QPS and approx. 78% (range 76-81%) for controlled uses. Of the total volume of MB consumed, including that for QPS, about 68% was for soil fumigation and approx. 32% was used on durable commodities, structures and perishable commodities (Figure 6.3).

The survey indicated that controlled uses comprised about 87% MB for soil fumigation (i.e. for treatment of soil before planting crops), approximately 12% for durable products and 1-2% for structures (excluding QPS). Figure 6.4 summarises the survey results for the soil sector, indicating that the major crops that utilise MB are tomato (24%), cucurbits (i.e. melon, cucumber and similar crops) (20%), tobacco seedbeds (20%), strawberry (15%), cut flowers and ornamentals (9%), peppers (3%), tree fruit (2%) and other crops (7%). Figure 6.5 presents the breakdown for the durables/structures sector, indicating that the major uses are stored grains (about 79%), other stored products (8%), food

Figure 6.3 Major applications of MB in Article 5(1) countries

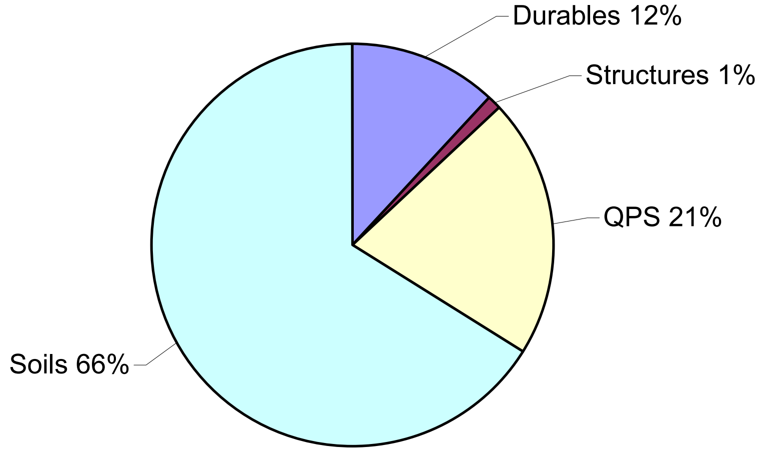


Figure 6.4 Soil sector: major crops utilising MB in Article 5(1) countries

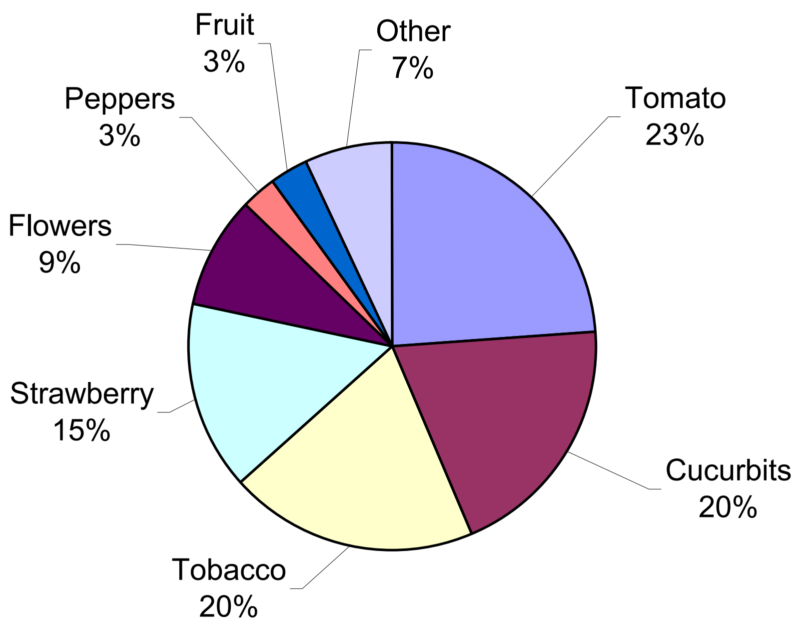
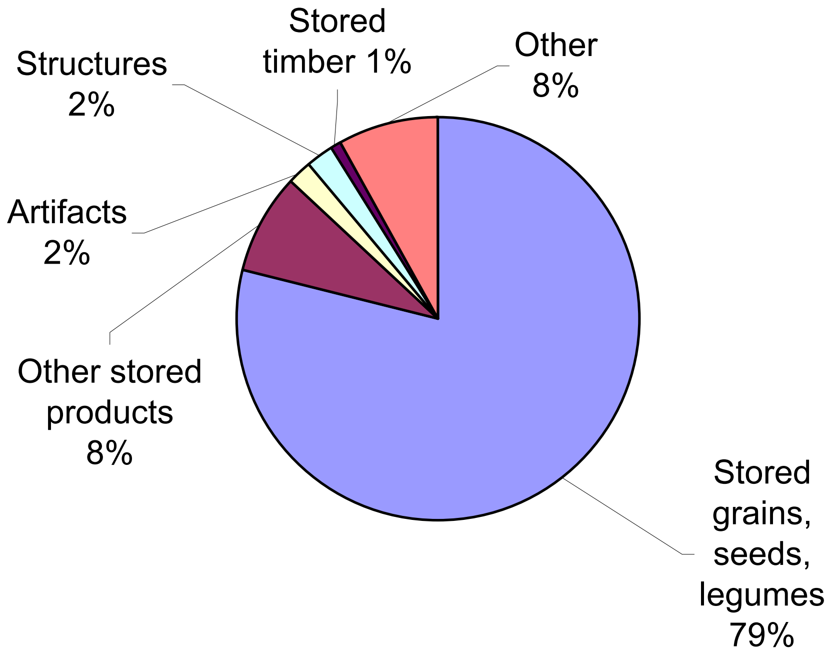


Figure 6.5 Major MB uses for stored durable products and structures – non-QPS applications in Article 5(1)



facilities/buildings/empty warehouses and transport (2-3%), artefacts (2%), stored timber (1%) and other or unidentified uses (7-8%), according to the survey responses.

6.3.6 Characteristics of MB use in Article 5(1) countries

MB users in Article 5(1) countries are diverse, ranging from small farmers (0.5 ha and less) to very large enterprises. There is also much variation with respect to the level of technical expertise, which is not necessarily correlated to the size of the operation, but possibly more to the destination of the crop - local market or export, the latter generally imposing stringent quality demands and in consequence being more technically demanding.

Consumption of MB is however not restricted to technically advanced enterprises. Simple, low technology methods of MB fumigation using one-pound MB canisters are available in many Article 5(1) countries. This situation has undoubtedly stimulated use of MB as it avoids the need for large and expensive injection rigs and professional applicators for soil treatments with MB.

6.4 Demonstration Projects

6.4.1 Objectives of demonstration projects

In 1997 the Parties to the Montreal Protocol decided to use MLF resources for identifying, evaluating, adapting and demonstrating MB alternatives in Article 5(1) regions, as stated in Decision IX/5(1b):

While noting that the overall level of resources available to the Multilateral Fund during the 1997-1999 triennium is limited to the amounts agreed at the Eighth Meeting of the Parties, immediate priority shall be given to the use of resources of the Multilateral Fund for the purposes of identifying, evaluating, adapting and demonstrating methyl bromide alternatives and substitutes in Parties operating under paragraph 1 of Article 5(1)….

As a result the MLF approved a number of demonstration projects. The main activities of demonstration projects were: trials to evaluate and adapt alternatives to local conditions, workshops with stakeholders, and dissemination of information to raise awareness about MB issues.

Demonstration projects aimed to transfer technologies to Article 5(1) regions from countries that already used alternatives, and established test plots on farms and research stations to evaluate and compare the efficacy (pest control), yields and practical viability of alternatives compared to MB. The intention was to test existing MB alternatives in the different climates and diverse agricultural practices and local conditions found in Article 5(1) countries. However, the demonstration projects did not aim to achieve actual MB reductions or phaseout. In response to Decision IX/5(1a) the Executive Committee of the MLF established a strategy and guidelines for MB projects (Multilateral Fund Secretariat, 2000). They stated *inter alia,* that:

The goal of demonstration projects should be demonstration of alternatives through a process that would facilitate wider understanding among users on how the alternative being demonstrated, if proven successful, might be applied to related uses throughout the country and perhaps throughout the surrounding region. (Decision 24/12. UNEP/OzL.Pro/ExCom/24/47. Multilateral Fund Secretariat, 2000).

The demonstration projects were not intended to carry out research nor to develop new alternatives, but only to evaluate existing alternatives transferred from other regions. Farmers, farmers' associations, other MB users, extensionists, national experts, agricultural ministries, government departments and other relevant stakeholders participated in the demonstration projects. National, regional and international experts assisted in transferring relevant expertise and know-how. In order to conduct the trials, the demonstration projects trained a small number of local farmers and other types of MB users, extensionists and local experts in alternative technologies. Demonstration projects were not intended to include extensive training of workers. Full technology transfer and comprehensive training of extension workers, farmers and other types of MB users in application of MB alternatives is carried out by phaseout projects that generally follow the demonstration projects.

The process of selecting alternatives for the trials was outlined by the guidelines of the Executive Committee of the MLF as follows:

Preparation of demonstration projects should commence with a participatory transparent process to identify all the promising alternatives for a specific target crop or use in a specific region, consistent with… the MBTOC report… Main users of methyl bromide for the specified uses should be brought together with relevant agricultural and environmental agencies, farmers who

> *have already used the likely alternatives and other stakeholders. Target pests should be determined by this group, and available alternatives should be considered in terms of their costs and benefits (including environmental impacts). The group should together select the alternative(s) to be field tested. In the controlled setting, which could be an existing respected agricultural research and demonstration facility, or a working farm setting, wherever practicable, these alternatives could be adapted to local conditions, applied, and evaluated. In order to produce results which might lead to widespread adoption of alternatives which prove successful, these demonstrations should be on plots sufficiently large to employ locally used practices and equipment…* (Decision 24/12. UNEP/OzL.Pro/ExCom/24/47. Multilateral Fund Secretariat 2000).

The projects generally drew on the 1994 and 1998 MBTOC Assessment Reports when they considered, at national level, which alternatives would be selected for evaluation in the trials. They covered a range of chemical and non-chemical techniques, as shown in Table 4. The demonstration projects focus on the alternatives relevant to Article 5(1) conditions. Some alternatives were trialled in research stations but in almost all cases alternatives were also trialled on working farms and/or by companies who use MB for stored products. Agricultural materials and equipment for alternatives were sourced locally where possible, but imported if necessary. In the case of floating seed-tray systems for tobacco seedlings, for example, substrates, seed-trays and plastics were procured locally or imported if necessary, and pilot-scale or full-scale float system beds were installed and evaluated. The equipment, materials and methods were adapted to suit local conditions as appropriate.

Projects normally concluded with workshops to discuss the results of the evaluation trials with growers, other types of MB users, extension staff, agricultural organisations, government departments and other stakeholders involved with MB usage. Detailed information and reports on the results of demonstration projects can be obtained from the implementing agencies and experts who carried out the projects. Some of the reports are now available on a joint website of UNEP/UNIDO, and other agencies also plan to publish project reports on the web.

6.4.2 Progress in the execution of demonstration projects

The MLF has approved 44 demonstration projects, and additional MB demonstration projects have been funded by other sources such as national governments, farmers and exporters' associations, as described in section 1 above. No further demonstration projects will be funded by the MLF.

A list of the demonstration projects appears in Table 6.3. The table gives the MB uses or crops involved, whether the project has been completed or is ongoing, and the agency responsible for the implementation of the project. About 29 of the MLF demonstration projects evaluated alternatives in the soil sector, covering all the major MB-using crops in Article 5(1) countries and specifically tomato, strawberry, cucurbits and tobacco. About 16 projects evaluated alternatives for post-harvest and structural uses of MB.

Table 6.3 Demonstration projects of the Multilateral Fund and other organisations

Country	Target MB sectors	Project Status	Agency
Argentina	Protected vegetables, tomato, flowers, strawberry	Completed	UNIDO
Argentina	Tobacco	Completed	UNDP
Argentina	Post-harvest cotton and citrus	Ongoing	WB
Botswana	Soil uses tomatoes and cucurbits	Ongoing	UNIDO
Brazil	Tobacco	Completed	UNIDO
Cameroon	Tobacco	Ongoing	UNIDO
Chile	Commodities	Completed	Canada
Chile	Tomato, pepper	Completed	WB
China	Stored grain	Completed	Canada
China	Tomatoes, cucumber, tobacco, strawberries, ginseng	Completed	UNIDO
China (a)	Technology transfer: tomato, cucumber	Completed	GTZ/Germany
China (a,b)	Strawberry, tomato	Ongoing	Italy
China (a)	Tomato, cucumber, other	Ongoing	GTZ/ Germany
China (a)	Tobacco	Ongoing	China
Colombia	Banana	Ongoing	UNIDO
Costa Rica	Melon (soil)	Completed	UNDP
Costa Rica	Flowers	Completed	UNDP
Croatia	Tobacco	Completed	UNIDO
Dominican Republic	Tomato, melon, tobacco, flowers	Completed	UNIDO
Ecuador	Flowers	Ongoing	WB
Egypt	Strawberry, tomato, cucurbits	Completed	GTZ/Germany
Egypt	Stored grain	Completed	GTZ/Germany
Guatemala	Broccoli, melon, tobacco, tomato, flowers	Completed	UNIDO

Indonesia	Stored products: milled rice, wood products	Completed	UNIDO
Jamaica	Post-harvest: tobacco	Cancelled	UNIDO
Jordan	Cucumber, tomato	Ongoing	UNIDO
Jordan	Soil uses, training	Completed	GTZ/Germany
Kenya	Stored grain	Completed	Australia/UK
Kenya	Flowers	Ongoing	UNIDO
Kenya	Stored grain	Ongoing	Canada
Lebanon	Tomato, cucurbits, eggplant, strawberry	Completed	UNDP
Macedonia	Tobacco, horticultural seedlings, vegetables	Completed	UNIDO
Malaysia	Stored timber	Ongoing	UNDP
Morocco	Tomato, cucurbits, training	Completed	GTZ/Germany
Morocco	Tomato, strawberry	Completed	UNIDO
Mexico	Tomato, strawberry, melon, flowers, tobacco	Ongoing	UNIDO
Mexico	Structures	Ongoing	UNDP
Philippines	Soil	Ongoing	UNDP
CEIT (a)	Tomato, cabbage, pepper, celeriac, strawberry	Ongoing	UNEP/ GEF
Senegal	Peanut seed	Completed	UNIDO
Sri Lanka	Soil: tea plantations	Completed	UNDP
Syria	Post-harvest and horticulture	Completed	UNIDO
Thailand	Stored grain: rice, maize, tapioca, feed grains, pulses	Completed	UNIDO
Tunisia	Post-harvest: dates	Completed	UNIDO
Turkey	Tomato, cucumber, flowers	Completed	UNIDO
Uruguay	Cucumber, pepper, tomato seedbeds, tobacco, nurseries	Completed	UNIDO
Vietnam	Stored grain, rice, silos, timber	Ongoing	UNIDO

Zimbabwe	Tobacco	Ongoing	UNIDO
Zimbabwe	Stored grains	Completed	UNDP

(a) Funded by organisations other than the MLF

(b) Technical transfer and capability building

6.4.3 Information exchange and awareness raising

Decision IX/5(1d) requested the Executive Committee of the MLF to consider ways to enable and promote information exchange on MB alternatives. The Executive Committee's strategy and guidelines on MB projects noted, *inter alia*, the important role of information exchange, creating and disseminating information and educating stakeholders (MLF 2000, 2001)

The MLF demonstration projects implemented by World Bank, UNDP, UNIDO and bilateral agencies included activities for awareness raising, information exchange and workshops with MB users and stakeholders. In addition, the MLF approved more than 50 projects for the development of information resources, information dissemination, awareness raising, and workshops for information exchange, policy or training. The resulting information resources included general information about MB, and technical resource books and manuals on suitable alternatives. Regional workshops and seminars were conducted in Article 5(1) countries with the aim of raising awareness, exchanging information about alternatives between farmers and experts, defining a basis for carrying out demonstration projects, farmer field schools, and training in policy development.

MBTOC did not attempt to quantify the impact of these informational activities. However Article 5(1) countries recognise that education and awareness have a significant impact in supporting ODS phaseout. Dependency on MB, for example, often results from a lack of knowledge on available alternative technologies and how to use them..

The exchange of information from Article 5(1) to Article 5(1) countries, from non-Article 5(1) to Article 5(1) and from Article 5(1) to non-Article 5(1) countries has been important in disseminating technical information about alternatives. Workshops were found to be more effective when the information transferred described specific country experiences on the use of alternatives particularly for countries that wanted to adapt them. For example, IPM approaches for cut flower production in Colombia are being adopted and adapted in projects in other countries in Latin America and Africa, where geographical and socio-economic conditions are similar (MBTOC 1998).

All these activities are helpful for replacement of soil uses of MB where most often, fumigation is in the hands of individual growers or grower groups. Post-harvest uses of MB pose a different situation, since treatments are normally carried out by storage and export/import companies or parastatals. The information shared about effective alternatives for these uses often influences decisions taken on what to use in future. Most importantly, raised awareness and information about MB alternatives has encouraged farmers, other MB users, agricultural organisations and government departments to examine alternative options, to reduce the frequency or application rate of MB where feasible, and to try to halt the spread of MB where possible.

MBTOC did not quantify the impact of information exchange and awareness programs on changes to MB use in Article 5(1) countries.

6.4.4 Alternatives tested in demonstration projects

A wide range of alternatives has been tested in demonstration projects, in many countries and climatic zones, both for soils and post-harvest uses. Table 6.4 summarises the main alternatives that have been tested for pre-plant, replant, seedbeds and nurseries on the most important crops using methyl bromide. Detailed technical information on these alternatives, their implementation and general efficacy against specific target pests is provided in Chapters 4 and 5 of this Assessment.

Table 6.4 summarises the alternatives that have been tested for post-harvest uses in the demonstration projects. Detailed information on these alternatives and specific target organisms may be found in this and previous MBTOC Assessment Reports (MBTOC 1995, 1998).

Table 6.4 Main alternatives tested for crops (soil uses) in demonstration projects in Article 5(1) countries

	Crops						
Alternatives	Strawberries	Tomatoes	Melons	Vegetables*	Flowers	Bananas	Tobacco**
Non-Chemical							
Biofumigation	CHI	CHI, GUA, LEB, MAC, MOR, TUR, URU	GUA, MOR, URU	LEB, URU	GUA, TUR		
Compost, organic amendments					COS, KEN		
Crop rotation		MOR	MOR				
Grafting		LEB, MOR	GUA, MOR				
Resistant varieties	TUR	CHI, MOR	MOR		SYR		
Solarisation	ARG, LEB	ARG, LEB, MOR, SYR, URU	COS	BRA,GUA	MEX		BRA, GUA

Soilless culture (substrates)	ARG, CHI				KEN		
Steam	ARG, CHI	MOR, JOR		GUA, ZIM (seedbeds)	ARG, COS, DOM, GUA, KEN, SYR, TUR, UGA		GUA, ZIM
Substrates in seedtrays		CHI		BRA, BOT, CAM, CHI, CRO, CUB, MAC, ZIM	DOM. GUA		BRA, BOT, CAM, CHI, CRO, CU, MAC, ZIM
Chemical							
Dazomet	ARG, LEB	CHI, GUA, LEB, URU	COS, GUA, MOR	BRA, CHI, MWI (seedbeds) URU, LEB	ARG, COS, DOM, KEN, MAC, MEX, TUR	COL, PHI	BRA, CHI, MWI
1,3-dichloropropene		MOR, TUR			MEX, TUR		
Metam sodium	ARG	ARG, GUA,	GUA,	URU	ARG, COS,		BRA,

		MOR, URU	MOR		DOM, KEN, MEX		CHI
Other chemicals Avermectin Formaldehyde Glyphosate		 CHI ARG 				 COL	
Combination Treatments							
Biofumigation + solarisation	CHI	BOT			DOM		
Dazomet + glyphosate						COL	
Dazomet + solarisation	CHI	CHI					
1,3-D + solarisation				LEB, TUR			
Metam sodium + 1,3-D/chloropicrin					MEX		
Metam sodium + EDB							ZIM
Metam sodium + solarisation		CHI	MEX				
Solarisation + organic amendments				GUA, LEB			BOT, CRO, LEB

ARG= Argentina; BOT = Botswana; BRA = Brazil; CAM = Cameroon; CHI = China; COL = Colombia; COS = Costa Rica; CRO = Croatia; CUB = Cuba; DOM = Dominican Republic; GUA = Guatemala; JOR = Jordan; KEN = Kenya; LEB = Lebanon; MAC = Macedonia; MEX = Mexico; MOR= Morocco; MWI = Malawi; PHI = Philippines; SYR = Syria; TUR = Turkey; UGA = Uganda; URU = Uruguay; ZIM = Zimbabwe.

* Peppers, cucumber, eggplant ** Floatation trays for seedling production.

Table 6.5 Main alternatives tested for postharvest uses in demonstration projects funded by MLF and other organisations

Alternatives	Dates	Dried fruit & nuts	Cocoa beans	Grain
Carbon dioxide	TUN			ZIM, SYR, TUN
Carbon dioxide + reduced pressure	TUN	TUR		
Carbon dioxide at high pressure		TUR		
Carbon dioxide + raised temperature		TUR		
Hermetic storage in flexible-transportable containers				ZIM, TUR, PHI, IND, INA, GHA, CHI
Vacuum-hermetic in flexible containers			IVC	
Nitrogen				ZIM
Phosphine			IVC	IND, SYR, THA, VIE, ZIM
Phosphine in carbon dioxide	TUN			IND, VIE

CHI = China; CHL = Chile; CYP = Cyprus; GHA = Ghana; INA = India; IND = Indonesia; IVC = Ivory Coast; MAL = Malaysia; PHI = Philippines; SYR = Syria; THA = Thailand; TUN = Tunisia; VIE = Vietnam; ZIM = Zimbabwe

6.4.5 Demonstration project results

The demonstration projects transferred alternatives used commercially in other countries and customized them to suit the specific local conditions. The projects have trialled a wide range of chemical and non-chemical alternatives, in diverse countries, climates, soil types and cropping systems, and for many different types of MB users and economic situations, ranging from small producers with less than 0.5 ha, to medium and large producers, who produce under low, medium and higher levels of technical sophistication (which does not necessarily correlate with size of operation). The projects selected and customised alternatives so that they would suit the needs and conditions of the different types of MB users.

In general, one or more of the alternatives tested in each crop situation have proven comparable to MB in their technical effectiveness for the control of pests and diseases. It is important to note that experts in charge of the projects and growers implementing alternatives, have frequently pointed out that these give best results when the alternative is a component of an integrated pest management program - basically including sanitation, disease-free propagation material and scouting to detect pests or diseases at the earliest possible stage. In many cases, combined alternatives have given the most effective results. The capability of adapting alternatives to a certain cropping environment and local conditions is essential to the success of any alternative. For example, locally available materials such as coconut coir and rice hulls have made it possible for many growers to use hydroponic systems usually requiring more sophisticated (or unavailable) materials such as rock wool or peat in developed countries.

Although some demonstration projects are still ongoing, more than 30 demonstration projects have been completed to date. The information available at this time allows for a general analysis on the efficacy of alternatives in different crops and locations. In some instances results were initially inconsistent, mainly due to application problems, but also to other factors as described below. However, in the majority of cases projects included a second phase where lessons learned from these first trials were considered and the most promising alternatives were tested further.

In some cases demonstration projects were delayed – sometimes substantially – with respect to their scheduled completion dates. There were various reasons for this – among them unexpected weather conditions requiring trials to be repeated, problems with delivery and installation of equipment or supplies, difficulties in establishing contracts and slow flow of information from the counterpart.

MBTOC requested experts in charge of projects completed to date to report their results to MBTOC in a standard format, so that the relative efficacy of alternatives and MB could be evaluated. A statistical analysis was provided in most cases. MBTOC made a comparative analysis of the results received for soil uses, by crop or crop group, and for post-harvest uses. Final project reports were the preferred data source, where available.

In the following sections, results for pre-plant and postharvest uses are analysed mainly with respect to their efficacy as compared to that of MB. More detailed information on these alternatives, recent research findings in both non-Article 5(1) and Article 5(1) countries, constraints to adoption and factors influencing their efficacy can be found in Chapters 4 and 5 of this Report.

A short definition, together with possible constraints to adoption when these exist, has been included for each of these alternatives. Commercial adoption of some of these alternatives is already occurring and this is summarised in Section 6.7 below. Detailed case studies on commercial adoption of different alternatives in many countries may be found in Chapter 9 of this Report.

6.4.6 Demonstration results for soil uses

Some alternatives, as with MB, aim to provide relatively sterile soil conditions (e.g. steam, substrates, alternative fumigants). Other alternatives focus on pest suppression, increasing soil biodiversity and encouraging competition between beneficial and harmful organisms. Even in those systems that provide relatively sterile soil, the soil may be reinoculated with beneficial organisms, e.g. by adding well made composts, after the treatment. This approach is gaining importance around the world. Although some proportion of the yield obtained when using soil fumigants such as MB may be lost when using suppressive and similar systems, enhanced biodiversity leads to more environmentally sustainable production.

6.4.6.1 Non-chemical alternatives

Solarisation Soil solarisation occurs when heat from solar radiation is trapped under clear, plastic sheeting to raise the temperature of moist soil to levels that are lethal to soil-borne pests (MBTOC 1998). It is a cheap and simple method that promotes beneficial organisms in soil and increases availability of some plant nutrients (Elmore *et al*. 1997, Katan 1996, Katan *et al*. 1998).

Results with solarisation have been very promising in many Article 5(1) countries and inconsistent in others:

Good control of nematodes (*Meloidogyne* spp.) attacking strawberries was achieved in the demonstration project in Lebanon (Hafez 2001). Similarly, adequate control of fungi (*Fusarium solani, Sclerotinia sclerotiorum*) in greenhouse tomatoes and carnations (*F. oxysporum*) was achieved in Argentina (Zembo *et. al.* 2000). Effects on greenhouse strawberries were highly dependent on location and climate in Turkey. Good control of soil fungi (*Pythium* spp., *Fusarium* spp., *Rhizoctonia* spp.) and weeds (*Cyperus* spp., *Portulacca* spp.) was obtained in some cases. (Benlioglu 2001, Yücel *et al.* 2001, Yücel *et al.* 2002). In selected locations, this alternative seems to have excellent potential for wide adoption in commercial strawberry production (Yücel *et al.* 2001, Yücel *et al.* 2002).

Furthermore, in some of these projects crop yields from solarisation were higher than those obtained with MB, for example in greenhouse tomatoes in Lebanon (Hafez, 2001) and open field broccoli in Guatemala (Calderón *et al.* 1999). This is most probably due to changes in the availability of certain plant nutrients and microbial populations in the soil (Porter *et al.* 2001).

Results from other demonstration projects indicate that solarisation provided good control of nematodes (*Meloidogyne javanica*) that attack tomato in Morocco (Ammati *et al.* 2002a), and also of nematodes affecting melons in Costa Rica (*Meloidogyne* spp.) (Chaverri and Gadea 2001a). Good control of nematodes (*Meloidogyne* spp.), fungi (*Phytophthora nicotianae, Rhizoctonia solani*) and several species of weeds in tobacco fields was reported in Cuba (Pérez *et al.* 2002a).

Mixed results were obtained with solarisation in tobacco seedbeds in Brazil, being best in southern tropical climates (Salles 2001). Solarisation is already being used widely at the commercial level in the Jordan Valley for protected cultivation of tomato, cucumber, pepper and strawberry, with excellent results (V. Hasse, 2002, pers. com.). However, in the Dominican Republic this alternative was not successful due to heavy rainfall during the season when it was trialled (Castellá and Gonzalez 2001).

Overall, solarisation is effective as an MB replacement under conditions of high and reliable solar radiation (sunlight) and if cropping cycles allow for a long fallow period (28 days or more). It is not suitable for all soil types and climates, and control of certain pathogens is insufficient. In consequence, for some intensive cropping systems where year-round production is economically important, such as cut flowers, it is generally not feasible as a sole treatment. Since climatic conditions cannot be guaranteed, some farmers claim that results of this option are too uncertain and therefore pose unacceptable economic risks in high value crops (UNIDO 1999). However, solarisation is feasible for certain climates, as illustrated by its successful commercial use in tomato and cucumber in the Jordan Valley (V. Hasse, 2002, pers. com.) and in certain melon production areas of Costa Rica (F. Chaverri, 2002, pers. com.). Also, when combined with other alternatives such as biofumigation or fumigants, results are much improved, risks lessened and treatment times are shortened.

Biofumigation. Biofumigation is the amendment of soil with organic matter that generates gases that control pests (MBTOC, 1998). This alternative has proven successful in countries such as Uruguay and its effectiveness in enhanced when combined with solarisation (see Chapter 9, Case study 2)

Weed control in open field tomatoes in Guatemala with biofumigation (chicken manure) varied according to location (Calderón *et al.* 1999). Control of root-knot nematodes (*Meloidogyne* spp.) and *F. oxysporum* in greenhouse tomatoes in China was not as effective as when using MB, but it was still possible to obtain 95% of the yield (UNIDO 2000).

Effective biofumigation is dependent on large amounts of organic waste and/or manure being available, which may limit its use in some locations. Further, the length of time that sometimes needs to be allowed for proper decomposition of the added organic materials can be a problem for some cropping systems. Treatment time can be reduced by combining biofumigation with solarisation.

Organic amendments. Organic amendments such as composts and green manure by-products from agriculture are used in many countries to control certain soil-borne pests in various crops (MBTOC 1998).

Compost increased yields of melons in Costa Rica in areas with low disease incidence, but application of very large quantities was necessary to obtain this effect. Further, it should always be used as part of an IPM system (Chaverri and Gadea 2001a). Organic manure, combined with deep digging, controlled *F. oxysporum* attacking greenhouse tomatoes in China with no significant differences with respect to MB (GTZ 2000). Initial results of compost application for reducing incidence of fusarium wilt (*F. o.* f. sp. *dianthi)* and other diseases of carnations in Kenya were inconsistent, possibly due to inadequate preparation of the compost (Pizano 2001).

Compost must be produced to stringent quality control standards. Aerobic conditions and appropriate temperature must be maintained to prevent the compost from partially fermenting and producing a sour medium containing organic acids that can be toxic to plants (MBTOC 1998). It is also dependent on large volumes of plant material being available, as high volumes need to be incorporated to the soil in order to obtain adequate results.

Composts from crop residues are used by the Colombian flower industry to amend soil and suppress problems caused by soil-borne pests for example *Pythium* spp. and *Fusarium* spp. At the same time, these crop residues provide plant nutrients and reduce production costs (Rodríguez-Kábana 1998, Pizano 2001, 2002).

Soilless culture (substrates). Soilless culture is a method in which substrates provide a pathogen-free anchoring medium that allows nutrients and water to be absorbed by plant roots. One purpose of using this system is to avoid soil-borne pathogens and thus the need for MB (MBTOC 1998).

Demonstration project trials with substrates have been mostly directed at the production of tobacco seedlings in floating trays. Results have been highly successful in Brazil (Salles 2001), Argentina (Valeiro 2002, Salles *et al.* 2001), Croatia (Turšić *et al.* 2001), Zimbabwe (Flower *et al.* 2000ab) and Senegal (UNEP/ UNIDO 2002). Excellent results with tobacco seedling production in floating trays were achieved in Macedonia for controlling fungi (*Fusarium* spp., *Alternaria* spp.), nematodes *(Meloidogyne* spp.) and weeds *(Amaranthus retroflexus, Chenopodium album, Cuscuta* spp. and others) (Popsimonova 2001). Similar results were obtained in China for controlling *F. oxysporum* and *F. solani* as well as *Meloidogyne* spp. (UNIDO 2000). Furthermore, yields were superior to those obtained with MB, since plant nutrition is better controlled (Popsimonova 2002a). Similarly, nematodes (*Pratylenchus* spp.), fungi (*Peronospora tabacina)* and various weed species were completely avoided in Guatemala (Calderón *et al.* 1999).

Although this alternative is not inexpensive, it has gained wide acceptance among farmers. In Cuba, of 790 farmers trained in recent years, over 250 initially adopted this technology with satisfactory results (Fernández *et al*. 2002). Through extension work, training was then further extended to nearly 2000 farmers, which have now adopted the system (Pérez *et al.* 2002b). Sixty percent of farmers in the Rio Grande do Sul state in Brazil presently produce tobacco seedlings in floating trays and this percentage is expected to increase in the near future (Salles 2001). Floating tray systems were identified as having potential for widespread adoption in China, if certain drawbacks could be overcome (Porter and Mercado 2000). Recently, the Chinese government has invested substantial funds in developing local substrates and floating systems that will lower costs of this alternative, and building greenhouses to avoid problems caused by low temperatures in early spring. As a result, the floating seed-tray system is being successfully and widely adopted at present in China, reducing MB needs (Cao 2002).

Trials with crop production, other than tobacco, in substrates have been conducted in some projects, e.g. Kenya where cut flowers were grown in pumice stone (Okioga *et al.* 2002, Pizano 2001) and Turkey, where tomatoes were grown in sand. The latter produced high yields, making this a promising option for that country (Ozturk *et al.* 2002). In Jordan, tomatoes and cucumbers were grown in tuff, and, although the system requires more experience before it can be applied commercially, the higher yields obtained are encouraging (Al-Zubi 2002). In China, control of *F. oxysporum* attacking greenhouse tomatoes grown on a peat/ vermiculite substrate amended with decomposed manure and fertilizer was comparable to that achieved with MB (GTZ

2000). Farmer trials also found that the production of nursery seedlings in substrate was effective in avoiding seedling diseases and nematodes. The cucumber yield using substrate-grown seedlings was significantly higher than normal soil cultivation and farmers found the technique very acceptable (GTZ 2000).

There is a commercial trend towards soilless cultivation in certain production sectors. including floriculture, protected strawberries and cultivation of vegetables around the world. For example, it was introduced in the early 90's as an alternative for the control of fusarium wilt of carnations in Colombia and presently about 25% of all flowers are grown in rice hull substrate (Salazar 2001). Some rose growers in Kenya are converting production systems to soilless culture in pumice and coco peat (Ammati and Nyambo 2001). Similarly, rose growers in Ecuador and Brazil are increasingly adopting this technique (Pizano 2002bc).

Although investment costs can be high, these are often compensated for by through increased yields and better quality. Costs are greatly reduced when locally available substrates are identified and production systems are adapted to local conditions (Pizano 2002a). Some substrate materials are re-used after being sterilized with steam (Gyldenkaerne *et al.* 1997).

This alternative requires growers to have good knowledge of plant/water relations and nutrition management. Also, clean water sources need to be available, or water cleaning systems need to be installed. Nutrient solutions used to fertilise the plants may also pose environmental hazards, being potential soil and water contaminants in certain types of substrate systems, although contamination can be avoided by using appropriate recirculating systems (Gyldenkaerne *et al.* 1997, Pizano 2001). Disposal or recycling of the exhausted polystyrene trays is an issue to be addressed in the near future.

Steam. Steaming is the introduction of water vapour at approximately 100º C where it kills soil-borne pests with the latent heat released when it condenses into water (Bungay 1999). During this process the soil temperature usually rises to 60-80º C. Where possible and practical, steam is a highly effective alternative to MB, having an equally wide spectrum of action and not requiring a waiting period before replanting (Gullino 2001, Miller 2001, Pizano, 2001).

Soil sterilisation with steam has been found successful in many demonstration projects, especially in the high value cut flower sector. Results comparable to MB were reported in Argentina for controlling fusarium wilt of carnations (*F. o.* f. sp. *dianthi*) although the particular method used in the demonstration was less efficient than MB for controlling fusarium rot of lisianthus (*Eustoma grandiflora*) caused by *F. solani* (Sangiacomo *et al.* 2000, Zembo *et al.* 2000, Salles *et al.*2001). Good control of *Pythium* root rot was achieved in snapdragons (*Antirrhinum* spp.) in Guatemala (Calderón *et al.* 1999; Solís and Calderón 2002) and of weeds (*C. rotundus*) and fungi (*Verticillium dahliae)* of lisianthus in the Dominican Republic (Castellá and Gonzalez 2001). In China, yields obtained from protected strawberry plantings grown on steamed soil gave yields similar to those normally obtained when using MB (UNIDO 2000).

Steam was also found to be successful in, for example, Costa Rica (Chaverri and Gadea 2001b) where control of *Fusarium* spp., *Rhizoctonia* spp. and *Pythium* spp. was comparable to that achieved with MB, and Kenya for controlling fusarium wilt of carnations (Pizano 2001). This alternative is being selected as the alternative of choice for most phaseout projects in cut flower sectors, for example Zimbabwe, Kenya, Uruguay and Uganda (see Section 6.5).

Investment costs may impose real limitations to widespread adoption of this alternative in Article 5(1) countries, except where MLF support is available. Steaming requires good technical expertise; otherwise phytotoxicity problems could arise for example due to overheating the soil (Miller 2001, Pizano 2001). Similarly to MB, steam creates a "biological vacuum" in the soil and should be used together with hygienic measures that help avoid recolonisation by pathogens. Inoculating the soil with beneficial organisms or incorporating organic amendments such as compost directly after treatment has been found useful in restoring beneficial soil microflora in Colombia (Rodríguez-Kábana 1998, Pizano 2001).

There are several steaming processes available. Negative pressure steaming, initially used in the Netherlands, has been used successfully in demonstration projects in Morocco (Ammati and Nyambo 2001, Ammati *et al.* 2002b). In certain instances, this system is quicker and cheaper as less fuel and energy are needed and is suited to a wider range of soils and situations than traditional (sheet) steaming (Barel 2002, Ammati *et al.*2002b).

Grafting. Grafting is a method that consists of using resistant rootstocks for susceptible annual and perennial crops to control soil-borne pests (MBTOC 1998). Grafting tomato plants onto resistant rootstocks provided adequate control of root knot nematodes (*Meloidogyne* spp.) in the demonstration project in Lebanon (Hafez 2001).

Wide commercial adoption of grafted tomatoes for controlling *F. oxysporum* f. sp. *lycopersici*, *V. dahliae* and *Meloidogyne* spp. has been reported in Morocco (Besri 2000).

6.4.6.2 Chemical alternatives

Most demonstration projects have evaluated the efficacy of MITC generators - dazomet and metham sodium - both as single treatments and combined with other alternatives, e.g. biofumigation or solarisation. Trials have also been conducted with other chemicals.

These chemicals are generally not new and have been in use for many years. In fact, several of them were at one time replaced by MB, both for efficacy and cost concern reasons (MBTOC 1995). Recently, however, improved application technologies, new formulations and using them within integrated management programs have increased their efficacy and reliability as alternative treatments for MB.

As with MB, concerns about possible long term environmental effects and health hazards should be taken into account when considering these products (MBTOC 1998).

Metham sodium. Metham sodium is a liquid broad-spectrum soil fumigant. Its high water-solubility makes it suitable for application by direct injection into the soil or via irrigation systems (MBTOC 1998).

Use of this fumigant has generally given good results in the demonstration projects. Successful weed control (various species) was achieved in open field tomatoes in Guatemala (Calderón *et al.* 1999) and in protected strawberries (*Cyperus* spp., *Portulacca* spp. and other species) in Turkey (Benlioglu 2001). Control levels of weeds (*C. rotundus* and *C. esculentus*) and fungi (*V. dahliae)* were not significantly different than those achieved with MB in *Liatris spicata* in the Dominican Republic (Castellá and Gonzalez 2001).

Metham sodium has also been used successfully in bananas in the Philippines against Moko disease caused by *Ralstonia solanacearum* (Mueller 2001). It was found to be one of the most promising alternatives for controlling many species of weeds in Costa Rican melons, mainly *Cyperus* spp. (Chaverri and Gadea 2001a).

Metham sodium has been widely used for many years in many countries, and is generally registered. It is also generally cheaper than other chemicals such as dazomet (by 40% in Argentina (Salles *et al.* 2001)). However, results using traditional application methods can be inconsistent because the soil needs to be adequately prepared and efficacy is dependent on moisture movement in soil as well as on certain factors like soil temperature, soil texture, organic matter content, pH and moisture (MBTOC 1998, Miller 2001). New application methods have improved its efficiency, and require technical know-how and appropriate equipment for soil preparation, injection and/or good dispersal in the soil, and sealing. Modern metham sodium application methods are being adopted in a number of Article 5(1) countries in MLF phaseout projects (e.g. application by injection with rotating spading techniques).

Dazomet. Dazomet is a granular pre-plant soil chemical. It requires uniform distribution in soil by mechanical means for good movement and efficacy (MBTOC 1998).

In demonstration projects it was successful for controlling weeds (various species) in open field tomatoes and melons in Guatemala (Calderón *et al.* 1999) and for fungi (*F. solani, S. sclerotiorum*) attacking tomatoes and open field strawberries in Argentina (Sangiacomo *et al.* 2000, Zembo *et al.* 2000). In protected strawberries, good control of nematodes (*Meloidogyne* spp.) was reported in Lebanon (Hafez 2001) and of weeds (*Cyperus* spp., *Portulacca* spp. and other species) in Turkey (Benlioglu 2002). Efficacy of this fumigant for controlling target nematodes, fungi and weeds was found to be comparable to MB in open field tobacco seedling production in Macedonia (Popsimonova 2001) and for nematodes (*Pratylenchus* spp.) in this same crop in Guatemala (Calderón *et al.* 1999). Control of *Meloidogyne* spp. and weeds in open field tobacco seedlings was not as good as that obtained with MB is China (UNIDO 2000), but control of *F. oxysporum* was similar to that obtained with MB. Excellent control of fusarium wilt of carnations and basal rot of *E. grandiflora* was also reported in Argentina (Zembo *et al.* 2000).

This fumigant has also given good results in other projects. In Poland, it was found to be a viable alternative to MB for strawberry and vegetable production (Slusarski and Pietr 2002). Its effectiveness for controlling vascular wilt (*F. o.* f. sp. *melonis*) and gummosis (*M. melonis*) of melons was found to be comparable to MB in the Dominican Republic (Castellá and Gonzalez 2001). However, it negatively affected tobacco seed germination in Brazil (UNIDO 1999) and Argentina (Salles *et al.* 2001).

Because it is available in granular form, dazomet is easier and less hazardous to apply than gases like MB and liquid chemicals such as metham sodium. These factors favour its adoption in Article 5(1) countries. However it requires soil preparation to allow good distribution, and application under sub-optimal conditions (i.e. wet and cold soils) may result in long waiting periods before replanting (Miller 2001). It is also relatively expensive in some Article 5(1) countries (UNIDO 1999).

1,3-dichloropropene. 1,3-dichloropropene (1,3-D) is a liquid fumigant highly effective against nematodes and most insects. It is less effective against weeds and pathogenic fungi than MB. The efficacy and range of action of 1,3-D can be enhanced by combining its use with other chemicals, such as chloropicrin (MBTOC 1998).

1,3-D has only been evaluated in a few demonstration projects. Good control of root-knot nematodes was achieved in protected cucumbers in Lebanon (Hafez 2001) and in melons in Costa Rica, where weeds (*Cyperus* and several other species) were controlled but application was considered difficult (Chaverri and Gadea 2001a).

Improved plant vigour and higher productivity were obtained with 1,3-D + chloropicrin alone or in combination with *Trichoderma viride*, suggesting these as possible replacements of MB for strawberry and vegetable production in Central and Eastern Europe (Pietr *et al.* 2000, Slusarski and Pietr 2002).

Registration constraints to this fumigant exist in some countries, particularly when formulations contain chloropicrin.

Other chemicals. Trials with other chemicals have also been conducted. These have mostly been directed at specific pests or diseases causing problems in a given crop. Avermectin was demonstrated for control of nematodes of tomato and cucumber in China (UNIDO 2000). The herbicide glyphosate, alone or in combination with dazomet, has been found efficient for controlling Moko disease (*R. solanacearum*) of bananas in Colombia. Affected banana plants are killed by the herbicide and this significantly reduces bacterial populations since they are highly specific for their host. In order to obtain adequate control, glyphosate should be used as part of an IPM program (Castañeda et al. 2002). Cadusafos proved comparable in its effect to MB for controlling nematodes of cucumbers (Meloidogyne spp.) in Lebanon (Hafez 2001).

6.4.6.3 Combined treatments

In many instances, demonstration projects found that combinations of treatments enhanced their individual efficiency and gave the best results. The most important examples reported in demonstration projects appear below.

Solarisation plus biofumigation The combination of solarisation plus biofumigation has proved successful in many countries and can reduce the time of treatment required by solarisation alone. The plastic traps the heat from solar energy raising the soil temperature and retaining gases generated during the biofumigation process (MBTOC 1998).

This combination has proven to be a very effective alternative to MB in protected peppers and tomatoes in Uruguay (Bernal 2001, Bernal *et al.* 2002), where different plant materials such as rice hulls, broccoli and corn debris have been trialled, proving similarly effective when compared to each other. In the northern region of Uruguay, where a high proportion of the pepper and tomato production of the country takes place, this alternative has been adopted by an estimated 20% of growers (R. Bernal, 2002, pers. com.). Some of them combine solarisation with metham sodium.

Excellent control of weeds (various species), fungi (*Fusarium* spp.) and nematodes (*Rotylenchulus* spp.) was achieved in melons in Guatemala as well as of fungi (*Plasmodiophora brassica*) and weeds (various species) in broccoli (Calderón *et al.* 1999). Good control of fungi (*Fusarium* spp., *Rhizoctonia* spp., *Pythium* spp.) was achieved in strawberries in Turkey (Yücel *et al.* 2001, 2002). Very good results were obtained in Uruguay at both trial locations for control of root knot nematodes in tomatoes (Bernal 2001).

Solarisation plus biocontrol agents such as *Trichoderma* successfully controlled fungi attacking strawberries (*Fusarium* spp., *Rhizoctonia* spp., *Pythium* spp.), and eggplant and peppers (*F. solani, S. sclerotiorum*) in Turkey (Yücel 2001, Yücel *et al.* 2002). Increased yields with respect to those obtained when fumigating with MB are also reported in these projects. For example, yields from tomato and strawberry crops following biofumigation with fresh chicken manure and solarisation were higher than those obtained with MB.

In other trials, good results were reported in melons in Costa Rica, where control of root-knot nematodes, weeds and soil fungi was comparable to MB in locations with appropriate climate and conditions (Chaverri and Gadea 2000a). Biofumigation plus solarisation is cheaper that MB in Jordan and a popular alternative among farmers. The combination seems to have excellent potential there as an MB alternative (V. Hasse 2002, pers.com). It is also used by about 40% of a total of 50 communities producing watermelons in the Mixtec region of the Mexican state of Puebla (Marban-Mendoza 2000).

Solarisation plus soil fumigants. Solarisation plus metham sodium was equally effective to MB for controlling nematodes of tomato (Meloidogyne spp.) in Uruguay (Bernal 2001, Bernal et al. 2002). Weed control (various species) was comparable to MB in open field tomatoes in Guatemala (Calderón et al. 1999). Root knot nematodes were efficiently controlled in protected tomatoes in Lebanon (Hafez 2001). Preliminary results of trials in China found excellent control of F. oxysporum with metham + solarisation in protected tomatoes (GTZ 2000).

In Morocco, the effects of solarisation were improved by combining this technique with metham sodium (with effects similar to those of biofumigation) and 1,3-D (Ammati and Nyambo 2001, Ammati *et al.* 2002ab). Similarly, solarisation plus 1,3-D, metham sodium or dazomet proved to be a promising alternative to MB for cucumbers and tomatoes in Turkey, with potential for commercial adoption (Ozturk *et al.* 2002). Preliminary results of trials on protected strawberry in China noted good results with low dose metham (35 g m^{-2}) via drip irrigation + solarisation against soil pathogens. The yield and vigour of the strawberry plants was not significantly different to MB (Cao *et al.* 2001).

In Kenya, dazomet applied at a reduced rate (42 g m^{-2}) in combination with solarisation, provided effective control of fungi (*F. o.* f. sp. *dianthi, Rhizoctonia* spp. and *Pythium* spp.), nematodes (*Meloidogyne* spp. and *Pratylenchus* spp.) and bacteria (*Erwinia* spp.). Plots treated with solarisation in combination with half doses of dazomet gave higher yields than yields obtained from plots treated with the full application rate (68 g m^{-2}) of MB (Okioga *et al.* 2002).

Combinations of chemicals. In Poland, a CEIT country, dazomet in combination with 1,3-D + chloropicrin gave wide-spectrum control of pests and diseases attacking strawberries, which was comparable to MB. This mixture may replace MB in strawberry plant propagation in Poland in the near future, and to a lesser degree in strawberry fruit production (Szczygiel 2002)

6.4.6.4 Feasibility of alternatives for soils

In addition to efficacy and crop yields, the projects also examined important aspects such as ease of application, relevance to climatic conditions and soil types, relevance to local cropping patterns, and commercial availability. For all crops tested, apart from ginseng replant, the projects identified at least one or more alternatives that were suitable for the types of climates, types of soil, production conditions, and the technical level of different types of MB users. Overall, the demonstration projects have covered a very wide range of conditions, soil types and crops.

In some cases alternative equipment and materials were not available locally when demonstration projects started, so the project had to import relevant materials. The subsequent MB phaseout projects are importing equipment and materials where necessary, and will encourage local manufacture and supply of these inputs so that commercial availability will be ensured for the long term.

Demonstration projects also evaluated the capital and operating costs of MB compared to alternatives. Some alternatives are generally cheaper than MB (e.g. solarisation), others are generally more expensive (e.g. dazomet), and others have similar costs. The costs vary substantially from one country to another because the input and labour prices vary for both MB and alternatives.

6.4.7 Results for postharvest uses

Demonstration projects have identified alternatives to MB for postharvest uses in many commodities and different countries. Table 6.6 presents a summary of these alternatives together with their efficacy relative to MB. More detailed information on some of these alternatives can be found in Chapter 5 (durable commodities). Projects generally concluded that alternatives should be implemented together with improved integrated commodity management programs.

Table 6.6 Performance of post-harvest alternatives tested in demonstration projects completed to date

Alternative	Commodities	Country	Efficacy with respect to MB	Comments
CO_2	Wheat, indoors Wheat, outdoors	Syria	** *	Sufficient quantities need to be available, may result in high cost

	Wheat/ maize Wheat/ maize in silos	Zimbabwe Kenya	* *	
CO_2 + reduced pressure	Dates, in chambers	Tunisia	**	
CO_2 + high pressure	Dried nuts and figs in chambers	Turkey	***	
CO_2 + raised temperature	Dried fruit	Turkey	***	
PH_3 + improved sealing where necessary	Milled rice Dates Wheat in silos (bulk) Wheat in sacks, outdoors Wheat, indoors Wheat, outdoors Wheat/ Maize Peanut seed	Indonesia Thailand Vietnam Tunisia Egypt Egypt Syria Syria Zimbabwe Senegal	*** *** *** *** *** *** *** *** *** ***	Longer treatment period (5 days). Some pests may develop resistance
PH_3 + CO_2	Milled Rice Wheat, indoors Wheat, outdoors Dates, freshly harvested	Indonesia Thailand Vietnam Syria Syria Tunisia	*** *** *** *** ** ***	Level of registration is limited, mostly due to high cost of gas cylinders

Hermetic storage in flexible-transportable containers	Paddy Milled rice Corn Spices	Philippines Philippines Philippines Bangladesh	*** *** *** ***	

*** Very effective; ** Effective; * Not effective

Carbon dioxide (CO_2). For effective insect control, periods longer than 10 days are often necessary, and it is essential to have very good sealing of enclosures or other means of maintaining sufficient gas concentrations (MBTOC 1998). At reduced pressure, this time can be halved. For this, very good sealing of treated enclosures is essential and re-dosing may be required. CO_2 was found to be equally effective to MB for controlling rice weevils (*Sitophilus oryzae*) in bagged wheat treated in storage sheds in Syria (Bell 2002).

The treatment requires local availability of sufficient quantities of CO_2 and may have a higher operating cost than some other treatments unless a cheap source of gas is available.

Carbon dioxide with low pressure and/or raised temperature. A demonstration project in Turkey identified combinations of CO_2 concentrations and raised temperatures that control the different stages of *Ephestia cautella*, *Oryzaephilus surinamensis* and *Trogoderma granarium* in dried fruit. For example, 70% CO_2 at 35°C was found to control diapausing larvae of *T. granarium* in about 30 hours. The high temperature is apparently critical for rapid action: other data at 30º C show that diapausing larvae of *T. granarium* can survive 17 days when exposed to this treatment (Spratt *et al*. 1985).

The project also identified combinations of low pressure and temperature that control various development stages of *Lasioderma serricorne* and *T. granarium*. Low pressure (25 mm Hg abs.) at 35°C, for example, controlled egg stages of *L. serricorne* in 75 hours and diapausing larvae of *T. granarium* in 172 hours (Navarro *et al*. 2002). Demonstrations in Turkey also found that the combination of high concentrations of CO_2 (about 96%) and raised temperature (30°C) provided effective disinfestation of *Plodia interpunctella* (larvae), *O. surinamensis* (adults and eggs) and *Carpoglyphus lactis* (mixed stages) in dried figs treated in flexible-transportable PVC cocoon containers (S. Navarro, 2002, pers. com.).

Phosphine (PH_3). This fumigant has been used worldwide for more than 40 years to disinfest a variety of commodities. It usually requires an exposure period of at least 5 days, which means it is suitable for stored commodities but not for products requiring faster treatment, unless treatment can be carried out earlier in the logistics chain. It is necessary to use a high degree of sealing and also the full exposure time to prevent further development of insect resistance to phosphine in some countries (MBTOC 1998).

Phosphine was found effective for controlling pests of stored grain in Thailand, when coupled with an integrated management approach based on good housekeeping, elimination of pest harbourages, cleaning, insect trapping and others (Melville and Tulvardhana 2001). In Egypt, phosphine was shown to be an efficient alternative to MB in grain storage, for the control of pests such as lesser grain borer (*Rhyzopertha dominica*), rice weevil (*S. oryzae*), flour beetles (*Tribolium castaneum*) and khapra beetle larvae (*T. granarium)*. A high level of sealing was essential for obtaining effective treatments (Gassert 2000). Phosphine was also found effective for stored grains in Indonesia, Senegal, Syria (Bell *et al.* 2000) and Vietnam, and for insect control in freshly harvested dates in Tunisia. Note, however, that although phosphine was effective technically, the longer turnround time of phosphine compared with MB poses major constraints on the quantity of dates that can be processed with existing receival facilities.

Phosphine plus carbon dioxide (PH_3 + CO_2). A mixture of phosphine plus carbon dioxide has been developed in cylinders but is currently used in only a few countries where registration has been applied for. It was found to be equally effective to MB for the control of rice weevil, *S. oryzae,* in bagged wheat treated in storage sheds in Syria, where highly skilled technicians and suitable infrastructure were available. Treatment outdoors was not as effective due to windy conditions (Bell 2002). The mixture was comparable in its effectiveness for controlling pests of stored grain in Thailand, (Melville and Tulvardhana 2001).

Constraints to wider adoption mainly centre upon the lack of registration. The high cost of cylinders of the mixed gas is likely to result in there being little if any incentive for the manufacturers to seek wider registration at present, particularly in Article 5(1) countries.

Vacuum-hermetic. Field trials in a demonstration project in Turkey found that low pressure (25-30 mm Hg abs.) created by a small vacuum pump attached to a sealed flexible (PVC) enclosure provided complete mortality of mixed stages of *E. cautella* and *T. castaneum* in 3 days (Navarro *et al.* 2002, Finkelman *et al.* 2002). A similar vacuum-hermetic system provided effective disinfestation of cocoa beans in trials in the Ivory Coast. Complete mortality of test insects was observed after 3 days. The efficacy against a wider range of pests normally associated with cocoa and other commodities is under investigation. Researchers reported that the system was economically viable, safer for operators than MB fumigation, and highly acceptable to purchasers (Navarro *et al.* 2002).

6.4.8 Uses of MB for which no alternatives were identified

The demonstration projects in China did not identify effective alternatives to MB for root rot in ginseng replant among the techniques tested (UNIDO 2000). Experts have identified several potential techniques that need to be trialled (V. Hasse, pers. com, 2002).

For the postharvest sector, MBTOC noted that the demonstration projects have identified one or more effective alternatives for each of the common stored products tested. However, the techniques tested to date did not identify rapid alternatives for controlling contamination with Carob moth larvae in dates directly received into storage at harvest. One of the implementing agencies is planning to trial further techniques for fresh dates in the near future.

6.5 MB Phaseout Projects

6.5.1 Overview of MB phaseout projects

The first MLF MB phaseout project was approved in 1998. By December 2002 the MLF had approved a total of 38 MB phaseout projects (mainly classified as 'investment' projects), which aim to phaseout major uses of MB in 35 Article 5(1) countries. These countries have opted for MB phaseout faster than the Protocol schedule mainly due to the following (Si-Ahmed 2002):

a) Effective alternatives are available;

b) Article 5(1) countries want to catch up with non- Article 5(1) in terms of new technologies and

c) Article 5(1) countries want to ensure continuity of exports and market access to non- Article 5(1) countries who may not accept products grown using MB after 2005.

The projects normally provide assistance for farmers and other MB users to adopt MB alternatives, by assisting with the procurement of alternative equipment and materials and by training large numbers of farmers/MB users and extension staff how to apply alternatives effectively. The projects also carry out other activities to overcome barriers to the widespread adoption of alternatives.

The project guidelines of the Executive Committee of the MLF have described MB phaseout (investment) projects as follows:

> *Projects whose primary objective is the reduction, and eventual elimination of methyl bromide consumption in sectors or for uses where there are clearly demonstrated efficacious alternative technologies. They should be accompanied by a package of policy measures that the country has committed to ensure that the use being phased out will not merely be replaced by an increase from other users shortly after the projects are completed (i.e. bans and import restrictions)…* (Decision 32/80. UNEP/OzL.Pro/ExCom/32/44. Multilateral Fund Secretariat 2001).

The development of policy measures is emphasised in the Executive Committee's guidelines:

> *It would also need to be demonstrated that the country concerned is committed to a package of policy measures directed to eliminating methyl bromide use (e.g., labelling of commodities produced without MB, taxes and levies on import of MB, mandatory registration by traders and farmers using MB, phase out schedule for MB) and to sustaining the alternative methodologies on a permanent basis or for as long as needed.* (Multilateral Fund Secretariat 2001).

The projects are typically executed by countries themselves with assistance from the implementing agencies UNDP, UNIDO and the World Bank, and several bilateral agencies (Germany/GTZ, Italy and France). Countries are only eligible for MB phaseout projects if they have ratified the Copenhagen Amendment of the Montreal Protocol, an amendment of 1992 which added MB to the list of controlled ozone-depleting substances (Ozone Secretariat 2000). The crops covered by projects approved to August 2002 are listed in Table 7 and 8. To date, 34 projects address uses of MB in the soil sector, such as strawberry, tomato, cucurbits, peppers, replant, cut flowers, tobacco seedbeds. Eight projects address post-harvest uses: stored grains, dried fruit and other stored products. Additional phaseout projects are currently being developed, with the aim of ensuring that all Article 5(1) Parties will be able to meet the MB freeze, 20% reduction step and phaseout commitment under the Montreal Protocol.

6.5.2 Alternatives selected in phaseout projects

National MB phaseout projects are adopting on a commercial scale the alternatives identified as effective and viable by demonstration projects and/or used in similar climates and conditions. For example, Jordan is introducing solarisation (within an IPM system, sometimes with the addition of biological controls, mainly *Trichoderma*) on a wide scale in suitable regions of Jordan, after identifying it as an effective alternative. The project is also trialling different alternatives for other climatic regions of Jordan, as part of a national project which will lead to the complete phaseout of MB. Likewise, Cuba identified floating trays + *Trichoderma* as an effective alternative for tobacco seedlings, and is now introducing this alternative on a wide scale in a MB phaseout project.

The Executive Committee guidelines for projects have outlined the following procedure for selecting alternatives in phaseout (investment) projects:

> *…workshops involving main stakeholders (such as methyl bromide importers, suppliers of alternative technologies, relevant government agencies, farmers and farmers' associations, fumigation companies using MB, research institutions/universities and NGOs), should be organised at the outset of activities in a country to decide on the most appropriate alternative technologies. The resource persons should be chosen as far as feasible from local experts or experts from close cultural areas to obviate any cultural barriers. Target pest should be determined and available alternatives should be discussed in terms of their costs and benefits, including environmental and human health impacts. The institutional capacity should be in place to enable the alternative technology used in an investment project to be adopted nation-wide. (Multilateral Fund Secretariat 2001).*

Table 6.7 identifies the main alternatives that countries have selected for adoption in their MB phaseout projects to date, as reported in the MLF Secretariat's reviews of projects and by the national experts involved in projects. For tobacco seedbeds, the prime alternative is floating trays. For cut flowers, the selected alternatives are steam + hygienic practices, 1,3-D, metham sodium, solarisation, substrates, dazomet and other chemicals used within IPM systems. For strawberry fruit, the alternatives selected for adoption in Article 5(1) regions include steam, solarisation + metham sodium or 1,3-D, solarisation + dazomet, solarisation + organic matter, solarisation + biological controls, and biofumigation. In the case of tomatoes, cucurbits, peppers, eggplant and other vegetables, the alternatives selected for adoption include solarisation + metham sodium, solarisation + 1,3-D, solarisation + dazomet, solarisation + organic matter, biofumigation, substrates, grafted plants, direct seeding, and steam + biocontrols for vegetable nurseries. In most cases the alternatives are being adopted with an IPM approach.

A number of Article 5(1) countries have developed strategies and workplans for MB phaseout that are being implemented as part of the MB phaseout projects. These strategies and methods provide useful models and show a way forward for other countries around the world. Experience to date in the MB phaseout projects has shown that it is feasible to rapidly train large numbers of farmers in the successful use of alternatives (Pérez *et. al.* 2002a, A. Valerio, pers. com, 2003). The projects have also overcome problems of lack of availability in the soil sector by initially importing the necessary equipment and materials, and then by promoting the local supply and/or manufacture of this equipment/materials, to ensure that the necessary inputs will be available to growers for the future.

Table 6.7 Soil alternatives selected for adoption in MLF phaseout projects (as at December 2002)

Crop	Alternatives selected for adoption	Region
Tobacco seedbeds	Floating tray systems	CEIT, Latin America, Africa, West Asia
	Floating trays + biological controls	Latin America
Cut flowers	Steam + hygienic practices	Africa, Asia, Latin America, West Asia
	Substrates	West Asia, Latin America, Africa
	Dazomet, 1,3-D, metham, other chemicals	West Asia, Africa
	Solarisation	Africa
Strawberry fruit	Steam + hygienic techniques	West Asia, Asia, Africa, Latin America
	Solarisation + dazomet, solarisation + metham, solarisation + 1,3-D, solarisation + manure, solarisation + *Trichoderma*	West Asia
	Dazomet	West Asia
Strawberry plant nurseries	Steam + hygienic practices	Africa, Latin America
	Dazomet	Latin America

Tomato, pepper, other vegetable crops such as eggplant, spinach, celery, lettuce, paprika, onion	Solarisation + organic amendments or manure, solarisation + metham or 1,3-D, solarisation + dazomet, solarisation + *Trichoderma*, biofumigation	CEIT, Latin America, West Asia, Africa
	Grafted plants	CEIT, Africa, West Asia
	Metham, 1,3-D, dazomet or other chemicals	Latin America, West Asia
	Substrates	Latin America, West Asia, North Africa
	Steam, steam + biocontrols	Latin America, Africa
	Direct seeding	West Asia
Cucurbits	Solarisation + metham, solarisation + dazomet, solarisation + other chemicals, solarisation + *Trichoderma*, biofumigation	Latin America, West Asia
	Metham, dazomet, cadusafos, oxamyl, other chemicals	Latin America, West Asia
	Grafted plants	Latin America, Africa, West Asia
	Substrates	West Asia
Seed potato	Steam + biological controls	Latin America
Banana	Steam, 1,3-D, metham, solarisation	Africa
Banana	Metham + glyphosate	Latin America
Fruit tree replant and tree nurseries	Steam, metham, 1,3-D, solarisation, biological controls	Latin America
Medicinal plants	Substrates	North Africa

Source of data: MLF Secretariat reviews of projects and documents supplied by the implementing agencies and national experts of the projects.

Alternatives selected for phaseout projects in the post-harvest sector appear in Table 6.8 These are as reported by the MLF Secretariat's reviews of projects and by national experts of projects. The alternatives selected for adoption to date are phosphine + integrated commodity management (ICM) for grains, peanut seeds, dried fruit and nuts; vacuum-hermetic storage for grains; and carbon dioxide + raised temperature and vacuum + raised temperature for dried figs and other dried fruit.

6.6 Scheduled MB Reductions

The projects approved to date (December 2002) are scheduled to eliminate about 8,000 tonnes MB in more than 35 countries, according to the agreements made between the MLF and Article 5(1) governments. In 19 countries, including some countries that consume large quantities of MB, the projects are designed to lead to early, full MB phaseout. In a further 16 countries they will eliminate major MB by about 2007/8, according to the needs of the country. The project funding is contingent on meeting a series of MB reduction steps specified in a written agreement between the national government and the MLF's Executive Committee. These written agreements often require Article 5(1) countries to phase out major MB uses much earlier than required by the Montreal Protocol schedule.

Table 6.8 Post-harvest alternatives selected for adoption in MLF phaseout projects (as at December 2002)

MB use	Alternatives selected for adoption	Region
Stored grains (e.g. wheat, barley, rice, maize, grain legumes, alfalfa seeds)	Phosphine + ICM, hermetic-vacuum storage	West Asia, Africa West Asia
Peanut seed storage	Phosphine + ICM	Africa
Dried apricots, dates, raisins, pistachio nuts, other nuts	Phosphine + ICM	West Asia
Dried figs, other dried fruit	Carbon dioxide + raised temperature, and vacuum + raised temperature in flexible-transportable containers	West Asia
Structural fumigation	Sulphuryl fluoride	Africa

Source of data: MLF Secretariat reviews of projects and information supplied by national experts of projects.

Table 6.9 lists the MB reductions that are scheduled per year by the phaseout projects approved to December 2002. It indicates that about 75% of the MB scheduled for phaseout in existing projects will be phased out before 2006.

The speed of planned MB reductions depends on a variety of factors, such as the initial consumption level, MB uses/crops and national policies. MB is scheduled to be reduced at an average annual rate of about 20% per year, in a total of 4.5 years on average (range 3-6 years). This includes countries that are small, medium and large MB consumers.

A number of additional MB phaseout projects are under development by the MLF and other organisations. The existing and anticipated projects are due to lead to the phaseout of about 10,000 tonnes MB before about 2007, eliminating more than 50% of the peak consumption of Article 5(1) regions.

Table 6.9 Timescale of MB phaseout scheduled in Article 5(1) countries in MLF phaseout projects approved to date (as at December 2002)

Period (years)	*MB scheduled for early phaseout (tonnes)*
1998 – 2002	1,529
2003 – 2005	4,455
2006 – 2008	1,990
Total	**7,974**

6.7 Alternatives Adopted at Commercial Level

MBTOC identified many situations where alternatives have been developed at commercial level, with clear potential for wider adoption. Table 6.10 lists examples of alternatives that in most cases were introduced by farms previously using MB for soil fumigation or post-harvest disinfestation. In some cases MB is still used but to a much lesser extent. Case studies in relation to these and other alternatives appear in Chapter 9 of this Assessment.

- Solarisation is widely used in farms in the Jordan Valley for protected cultivation of tomato, cucumber, pepper and strawberry, with excellent results (V. Hasse, pers. com. 2002). The melon sector of Costa Rica has adopted this alternative for weed and pest control in over 500 ha of the production (F. Chaverri, pers. com, 2002, Case study 9). It has also shown wide commercial potential for controlling broomrape (*Orobanche ramosa)* in melons grown under plastic tunnels in Morocco (Case study 10).

- Despite the initial high investment required for floating seed-tray systems for tobacco seedlings, they have gained wide acceptance among farmers. In Cuba, about 2000 farmers trained through extension have already adopted this technology with satisfactory results (Pérez *et al.* 2002b, Case study 19). 60% of farmers in Rio Grande do Sul, the major tobacco-producing state of Brazil, presently produce tobacco seedlings in floating trays and this proportion is expected to increase in the near future (Salles 2001). The tomato sector in this country has also adopted this technique. By 2001, about 20% of the tobacco sector in Croatia had adopted floating trays, and it is expected to grow to 30% in 2002 (Turšić and Hamel 2002). A number of small and medium-scale tobacco producers in Argentina have adopted floating trays as a result of MLF projects (A. Valeiro, pers. com., 2002, Case study 17). The floating seed-tray system is also being successfully and widely adopted in China (Cao 2002).

- Adoption of soilless cultivation is becoming a significant commercial trend in some intensively produced crops in many countries, e.g. cut flowers, strawberries and vegetables. For example, about 25% of all cut flowers grown in Colombia are presently grown in substrates (Salazar 2001, Case study 21) and some rose growers in Kenya are converting production systems to soilless culture in pumice and coco peat (Ammati and Nyambo, 2001).

- In Morocco grafting + metham sodium, together with cultural practices such as sanitation, organic amendments, etc, have been widely adopted at the commercial level for tomato (Besri 2000, Case study 4). The potential for use of grafting in Lebanon has been reported as excellent.

- Biofumigation plus solarisation is cheaper than MB in Jordan and a popular alternative among farmers that has real potential for further adoption (V. Hasse, 2002, pers. com.). Solarisation alone or in combination with biofumigation or metham sodium has been very successful in Uruguay where, as a result, around 20% of commercial tomato and pepper growers in the main production area have adopted biofumigation and related techniques (R. Bernal, 2002, pers. com., Case study 7). Biofumigation + solarisation is used commercially in Macedonia in some greenhouses producing tomato and cucumber and, following successful demonstration results, will be widely adopted in the vegetable sector (Popsimonova 2002b, Case study 2).

- Soil amendments + mulch are used by about 40% of a total of 50 communities producing watermelons in the Mixtec region of the Mexican state of Puebla (Marban-Mendoza 2000).

- In the stored grain sector, phosphine is used in many Article 5(1) countries (MBTOC 1998), such as Indonesia and Vietnam (case study 22). Modified atmosphere treatments are also being adopted in some countries. For example, Turkey is adopting carbon dioxide + raised temperatures for dried fruit (S. Navarro, pers. com., 2002). Cyprus uses hermetic storage for more than 216,000 tonnes of stored grain (A. Varnava, 2000, case study 24). Modernised hermetic storage has been adopted commercially in the Philippines, India, Ivory Coast (Case study 23) and the West Asia for stored paddy, milled rice, maize, wheat and seeds (Navarro *et al.* 2002).

Commercial trends to reduce the environmental impacts of pesticides in agriculture may increasingly affect Article 5(1) producers of export crops. Consumer concerns have led to the development of special agricultural production standards and eco-labels that establish environmental (and sometimes social) standards, including measures to reduce the use of pesticides. Some such labels or programs are starting to prohibit fumigation with MB as a condition of meeting the standards. In the cut flower sector, for example, the MPS (Milieu Programma Sierteelt) environmental grade standards have been adopted by about 5,000 farms in 22 countries, including Costa Rica, Ecuador, France, Italy, Israel, Kenya, Netherlands, USA, Zambia and Zimbabwe. Growers who participate in the MPS system are generally not permitted to use MB (de Groot, pers. com., 2001). Another example is FLORVERDE, the environmental program of the Colombian flower industry, which requires careful monitoring of all chemicals used in the production process and prohibits use of some compounds among them methyl bromide (ASOCOLFLORES 1998). European supermarkets have developed ‘EUREP-GAP’ agricultural production standards for fruit and vegetables, aiming to decrease environmental impacts and raise consumer confidence. *Inter alia*, EUREP-GAP requires any MB fumigation to be justified in writing and used only as a last resort; growers have to demonstrate that they have explored alternatives. EUREP-GAP discourages use of MB in a voluntary way at present, but this may become compulsory in future (Moeller 2002). Sainsbury's supermarket chain in Europe specifically prohibits its suppliers from using MB in certain crops. Two other supermarket chains in the UK have announced new codes of practice which will prohibit the use of MB and certain other pesticides by suppliers, as a result of consumer concerns about the environment (Buffin 2001ab).

Table 6.10 Examples of MB alternatives introduced commercially in Article 5(1) countries.

Alternative	Crops	Pests controlled	Examples of countries where adopted commercially
Floating trays	Tobacco	Weeds (*Amaranthus* spp., *Cynodon* spp., *Cuscuta* spp., *Portulacca* spp and others). Fungi (*Fusarium* spp., *Pythium* spp.). Nematodes (*Meloidogyne* spp.)	60% growers in southern Brazil
	Tomato	Bacterial wilt (*Ralstonia solanacearum)* fungi (*Fusarium* spp., *Verticillium dahliae, Phytophthora infestans)*, Weeds (*Cyperus* spp and others)	Widely adopted in Argentina and Cuba and by larger tomato growers in Brazil Good adoption in Macedonia, China
Solarisation + Biofumigation	Peppers, tomatoes	*Nematodes (*Meloidogyne *spp.*), *Fungi (*Phytophthora *spp.*, Fusarium *spp.*, Verticillium *spp.) Weeds (various species)*	20% of growers in north Uruguay Use is expanding in Macedonia
Soilless substrates	Carnations	*Fusarium oxysporum* f. sp. *dianthi*	25% of flower growers in Colombia
	Roses	Rose replant, Nematodes *Meloidogyne* spp.	Adoption increasing in Kenya, Ecuador, Brazil

Solarisation	Melon	Broomrape (*Orobanche ramosa)* Weeds (*Cyperus* spp.*),* Nematodes (*Meloidogyne* spp.*)* Fungi	Potential in Morocco 10% of melon sector in Costa Rica
	Tomato, Pepper	Nematodes (*Meloidogyne* spp.)	Widely adopted in Jordan
Grafting and Metham sodium	Tomato	*Fusarium oxysporum* f.sp. *lycopersici* (races 1 and 2), *Verticillium dahliae* (races 1 and 2), *Meloidogyne* spp.	Wide commercial adoption in Morocco
Metham sodium + glyphosate and IPM	Bananas	Moko disease (*Ralstonia solanacearum,* race 2)	MB has been phased out from this sector in Colombia
Phosphine	Stored milled rice, wheat, maize and other grains	Beetles including *Sitophilus* spp., *T. castaneum*, *O. surinamensis, R. dominica, Ahasverus advena and Cryptolestes minutus*. Moths including *Corcyra cephalonica*.	Worldwide commercial adoption

6.8 Conclusions

MBTOC concluded that trials and demonstration projects have played a useful role in identifying alternatives that are suited to the production environments in Article 5(1) regions. For the major crops where MB is used, the demonstrations successfully tested and evaluated a wide range of chemical and non-chemical alternatives in research plots and under full field conditions. They assessed the efficacy of alternatives with respect to target pests, suitability to the diverse climatic conditions, soils and cropping patterns in Article 5(1) countries. The projects also evaluated important factors such as the ease of application, commercial availability and economic costs and viability. The trials covered diverse countries and many different types of MB users and economic situations, ranging from small producers with less than 0.5 ha, to medium and large producers, who produce under low, medium and higher levels of technical sophistication (not necessarily correlated to the size of operation). About 29 demonstration projects evaluated and customised alternatives in the soil sector, covering the major crops such as tomato, strawberry, curcurbits, cut flowers and tobacco grown in Article 5(1) conditions. About 16 of the projects (completed and on-going) evaluated alternatives for postharvest uses of MB, such as stored grains, pulses, peanut seeds and dried fruit. These activities identified effective, viable alternatives for the vast majority of uses in Article 5(1) countries, and also demonstrated it is feasible to adapt and implement alternatives successfully within a couple of years in Article 5(1) countries.

Demonstration projects showed the importance of utilizing new, effective application methods for alternatives, and the need for transference of appropriate know-how. Demonstration trials have assisted countries and productive sectors to adapt alternatives to their specific situation, and to develop alternative methods that use materials or infrastructure that are locally available, in order to make them applicable and cost effective. Thorough training of farmers/MB users is essential to ensure that alternatives will be applied properly and effectively, and for the widespread adoption of alternatives to occur. This is especially urgent in view of farmers in some countries being used to simple, low technology methods such as one-pound MB canisters. The MLF and bilateral agencies are assisting countries with necessary technical and financial resources to continue the task of transferring and adapting alternatives, training large numbers of farmers and MB users, and developing policy measures to support the MB phaseout.

By December 2002 the MLF had approved a total of 232 MB projects in more than 60 countries. This includes 44 demonstration projects, 38 phaseout projects and about 150 other projects for information exchange, awareness raising, policy development and project preparation, etc. Additional activities to trial and/or introduce alternatives have been funded by Article 5(1) governments and/or agricultural producers (e.g. in China, Kenya, Lebanon, Morocco), and by bilateral assistance from governments (e.g. Australia, Germany/GTZ, Italy, Canada) and the GEF.

6.8.1 Successful replacements of MB, by crop.

It is apparent that one technology, alone, will not replace all uses of MB: a range of technologies is needed to replace the diverse uses of MB. As stated previously, factors relating to application method, climate, soil type, target pests, geographical location and others, clearly influence the efficiency of alternatives, so it is necessary to select the most appropriate technique for each situation. Further, the capability of adapting alternatives to a certain cropping environment and local conditions is essential to success. For example, locally available materials such as coconut coir and rice hulls have made it possible for many growers to use hydroponic systems usually requiring more sophisticated (or unavailable) materials such rock wool or peat in developed countries. Further adaptations and improvements of this kind are being implemented in MB phaseout projects.

The situation for Article 5(1) alternatives is summarised below, by crop, outlining the most effective alternatives identified by trials and demonstration projects, examples of alternatives used commercially on farms, and a summary of the alternatives that have been selected for adoption in MLF phaseout projects for major crops/uses of MB.

6.8.1.1 Tobacco seedbeds

The demonstration trials concluded that the float system is an effective MB alternative, applicable to many regions where tobacco is grown. In some countries, effective results were also achieved with dazomet and dazomet + solarisation. The tobacco-producing countries that are now implementing MB phaseout projects have primarily chosen to adopt floating tray systems. Adoption of this technique is presently increasing in countries like Brazil, Cuba, Zimbabwe, Argentina, Macedonia, Croatia and China (see also Case studies 17,18).

6.8.1.2 Cut flowers

The demonstrations identified steam + sanitation practices, metham sodium, substrates and dazomet, as effective alternatives to MB. Countries implementing phaseout projects in the cut flower sector have chosen to adopt these same treatments.

Steam + organic amendments are used commercially in Colombia and Costa Rica, for example. Commercial adoption of substrates in greenhouse flower production is increasing in Colombia, Brazil, Ecuador and many other regions (e.g. Case study 21).

6.8.1.3 Tomato, cucumber, melon, peppers, eggplant and other vegetables

The demonstrations identified solarisation, solarisation plus biofumigation, solarisation + metham sodium or dazomet and grafting, as treatments with effects comparable to MB for the control of soil-borne pests and diseases.

Examples of commercial adoption of solarisation alone or in combination with metham sodium or biofumigation include a significant number of tomato and pepper growers in Uruguay (Case study 7). Solarisation and biofumigation are widely used by tomato and cucumber growers in the Jordan Valley. Use of tomato plants grafted onto rootstocks that are resistant to key fungal pathogens and root-knot nematodes is now a common practice among farmers in Morocco and it is very likely that the same will soon be the case in Lebanon.

Countries that are implementing MB phaseout projects for vegetables/melons, have chosen to adopt alternatives such as solarisation + metham or 1,3-D or dazomet, solarisation + organic matter, biofumigation, substrates, grafted plants, direct seeding, and steam + biocontrols for vegetable nurseries (e.g. Case studies 2,9,10).

6.8.1.4 Strawberries (fruit production)

Demonstrations identified metham sodium, dazomet, solarisation and solarisation in combination with either of these two fumigants as effective alternatives to MB for Article 5(1) conditions.

Solarisation alone or in combination with biofumigation or *Trichoderma* was reported as having high potential for wide commercial adoption in Turkey. Dazomet + 1,3-D and chloropicrin are being adopted in countries like Poland at the commercial level.

Countries who are implementing MB phaseout projects in the strawberry sector have chosen to adopt alternatives such as solarisation + metham sodium or solarisation + manure and *Trichoderma*. Biofumigation + 1,3-D and steam have also been selected, the precise combination of techniques depending on the climate, the soil type and target pests.

6.8.1.5 Banana and fruit trees

Dazomet has proved an efficient alternative to MB for controlling Moko disease of bananas. This chemical is now widely used commercially in banana plantations in countries like Colombia and the Philippines. Metham sodium combined with IPM is used in Colombia (Case study 3).

Countries who are implementing MB phaseout projects for banana plan to adopt combinations of steam, 1,3-D, metham or solarisation. For fruit trees, Article 5(1) countries plan to adopt alternative fumigants + selected chemicals for replant problems, and steam or steam + biocontrols for fruit tree nurseries.

6.8.1.6 Postharvest

Many former uses of MB in Article 5(1) countries have already been replaced by phosphine, as noted in previous MBTOC (1995,1998) reports. Compared to the soil sector, there was a smaller range of alternatives available for testing in post-harvest demonstration projects. In most cases the current choice of alternatives treatments lies between phosphine, carbon dioxide, combinations of these gases with raised temperatures and high or low pressures, other modified atmosphere systems, and vacuum-hermetic treatments. While the limited choice at present may be cause for concern – dependence on a few processes is not good strategically – the range of available alternatives is expected to increase in the next few years when several new fumigant products are likely to be registered. However, the techniques available at present can achieve effective disinfestation in virtually all stored products that do not need QPS treatments.

The paragraphs below summarise the results of the postharvest demonstration projects, examples of commercial use of alternatives, and alternatives selected for phaseout projects.

Stored grains, pulses, dried fruit and nuts. Phosphine has been identified as a suitable alternative to MB for these commodities. The demonstration project on grains in Egypt, for example, concluded that phosphine (combined with improved gas-tightness) is an effective and viable alternative for bagged grains (bag stacks), silos and warehouses. In Syria, CO_2 was found to be an efficient alternative in bagged wheat, and control of pests attacking stored grains in Thailand with a combination of carbon dioxide + phosphine was comparable to MB. Vacuum-hermetic treatments were found to provide 3-day alternative treatments for durable commodities in Turkey and Côte d'Ivoire, for example.

Countries who are implementing MB phaseout projects have chosen to adopt phosphine + ICM for stored wheat, maize, rice and peanut seeds. Additionally, for dried fruits and nuts, they have chosen carbon dioxide + raised temperature.

Phosphine is used commercially in many Article 5(1) countries. Hermetic storage has been adopted commercially in the Philippines, India, West Asia and Cyprus for stored paddy, milled rice, maize, wheat, barley and seeds. Vacuum-hermetic systems are also being introduced.

6.8.2 Crops for which alternatives were not identified

The demonstrations did not identify an effective alternative for control of ginseng root rot for replant in China nor a rapid alternative disinfestation technique for fresh dates at point of receival after harvest in North Africa. In both cases, potential alternatives have been noted and need to be tested.

6.8.3 Progress in MB reductions

The results analysed indicate that substantial progress has been made in the identification of suitable alternatives in Article 5(1) regions. The consumption of MB in Article 5(1) countries was reduced from 17,595 tonnes in 1998 to 16,438 tonnes in 2000. The MB phaseout projects currently underway will phaseout major uses of MB (and in some cases all uses of MB in the country, except for QPS), and reduce Article 5(1) MB consumption by about 5,470 tonnes. The projects are scheduled to phaseout more than 70% of this by 2005, and about 82% before 2006, making step-wise MB reductions throughout the projects.

The speed of scheduled MB reductions depends on a variety of factors, such as the initial consumption level, MB uses/crops and national policies. In the countries that plan 100% elimination, MB is scheduled to be reduced at an average annual rate of about 22.5% per year, in a total of 4.4 years on average (range 3-6 years). This includes countries that are small, medium and large MB consumers. Experience in implementing projects to date has shown that alternatives can be adopted within a relatively few years in Article 5(1) countries.

Additional MB phaseout projects are under development by the MLF and other organisations. The existing and anticipated projects are due to lead to the phaseout of about 10,000 tonnes MB before about 2007, eliminating more than 50% of the peak MB consumption in Article 5(1) regions.

The MLF activities described above indicate that it will be feasible for Article 5(1) countries to make additional, substantial MB reduction steps before 2015, provided that the necessary MLF support continues for countries that need technical and financial assistance. Experience with demonstration and phaseout projects shows that the technical, climatic, social and economic barriers to MB alternatives can be overcome successfully for major MB uses in diverse Article 5(1) regions.

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Chapter

7

Alternatives to methyl bromide for quarantine and pre-shipment applications

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7.1 Introduction

Quarantine and pre-shipment (QPS) treatments can be applied when necessary to kill pests on perishable and durable commodities. Typically QPS treatments with methyl bromide (MB) are applied to commodities in trade. *Perishable* commodities include fresh fruit and vegetables, cut flowers, ornamental plants, fresh root crops and bulbs. *Durable* commodities are those with low moisture content that, in the absence of pest attack, can be safely stored for long periods. They include foods such as grains, dried fruits and beverage crops and non-foods such as cotton, wood products and tobacco.

The consumption of methyl bromide (MB) for QPS is not controlled under the Montreal Protocol. That is, QPS consumption is currently exempt under Article 2H para.6 from all Protocol controls such as a freeze, reductions in consumption and phaseout.

Although there have been some implementation of alternatives to MB for QPS uses since the last MBTOC Assessment in 1998, notably on timber and wooden packaging, the majority of the effort on QPS alternatives continues to be research orientated and therefore this chapter largely focuses on the key research efforts underway to find non-MB QPS treatments. The Protocol's Technology and Economic Assessment Panel (TEAP) has previously provided an extensive report on QPS, including examples of treatments considered by TEAP to be QPS (TEAP 1999, TEAP 2002), QPS consumption, QPS alternatives, prospects for recovery, containment and recycling of MB used for QPS and QPS relationship to other conventions and treaties (TEAP 1999). The key conclusions of these reports are also included in this chapter.

Specific sections in this chapter:

- Examine the definitions of QPS and the relationship of these terms to other international plant conventions and organisations (Sections 7.2 and 7.3);

- Review national legislation that more strictly governs the use of MB for QPS than the Montreal Protocol (Section 7.4);

- Report on the various applications of MB for QPS and consumption of Mb for these applications (Sections 7.5);

- Discuss constraints limiting the development of alternatives (Section 7.6) and research opportunities where alternatives were not identified (Section 7.11);

- Discuss firstly, the key features of the technologies that can replace MB (Section 7.7); and secondly, cover the existing and potential use of this technology for key perishable (Section 7.8) and durable commodities, transportation vehicles, museum artefacts and miscellaneous uses (Section 7.9); and thirdly, summarise Sections 7.6, 7.7 and 7.8 in three tables (Section 7.10);

- Discuss opportunities to reduce emissions from QPS uses of MB (Section 7.12); and

7.2 The Use of Methyl Bromide for Quarantine and Pre-shipment

Many perishable and durable commodities in trade and storage can be attacked by pests, including insects, mites and fungi, causing loss of quality and value. These commodities may also carry pests and diseases that can be a threat to agriculture, health or the environment. There are a wide variety of measures that can be taken to manage these pests so that the damage they cause or risk that they pose is acceptable. Fumigation with MB is one such measure.

Most current uses of MB on durables and perishable commodities worldwide are highly specialised. MB use has been in routine use for decades as a well-developed system with a good record of successful use. In such cases, prior to MB phaseout because of its ozone-depleting properties, there was little reason to adopt alternative practices. Some examples of valid QPS uses include:

- Fumigation of cut flowers found to be infested on arrival in the importing country with quarantine pests (quarantine treatment);

- Fumigation of fruit before export to meet the official phytosanitary requirements of the importing country for mandatory fumigation of an officially-listed quarantine pest (quarantine treatment);

- Fumigation of grain before export to meet the importing country's existing import regulations that require fumigation of all export grain consignments (pre-shipment treatment);

Further examples of treatments that may be QPS were provided in the TEAP 1999 and TEAP 2002 reports.

Requirements for MB alternatives are often compared with MB's properties which include such desirable features as:

- Rapid speed of treatment. This is particularly useful for perishable products that must be marketed rapidly;
- Low cost for fumigation
- Relatively non-corrosive and applied easily to shipping fumigation facilities, containers or to bagged, palletted or bulk commodities 'under sheets';
- A long history of recognition as a suitable treatment by quarantine authorities;
- Broad registration for use;
- Good ability to penetrate to the into the commodity where pests might be located; and
- Rapid release of gas from the commodity after exposure;

MB also has a number of undesirable features including:

- A high level of toxicity to humans;
- Odourless, making it difficult to detect;
- A significant ozone depleting potential;
- Adverse effects on some commodities, particularly loss of viability, quality changes and taint; and
- Chemical residues retained in the product.

Dosages of MB at 80-200 g h m^{-3} mainly control insects, mites and vertebrate pests but higher rates typically exceeding 5000 g h m^{-3} are required for control of nematodes, snails and fungi; and for devitalising seeds.

MB has a long and successful history as a QPS fumigant. In many situations, it is the only treatment approved by national quarantine authorities. MB fumigation for pre-shipment may be selected when the commodity must be treated more rapidly than is possible with phosphine fumigation, the main current alternative. Quarantine treatments are supported by extensive scientific data documenting the responses of pests to MB as these data are required to verify a high level of treatment efficacy for pests that are considered to be serious threats to the agriculture of the importing country.

These treatments come under a number of international and national agreements and regulations, including particularly the International Plant Protection Convention (IPPC) and its regional bodies, as well as various national quarantine regulations. The reader may wish to consult the following websites as examples of international and national plant protection guidelines, regulations and treatments for perishable and durable commodities:

- International Plant Protection Convention (http://193.43.36.94/cds_ippc/IPP/En/default.htm)
- European and Mediterranean Plant Protection Organisation (http://www.eppo.org)
- The Ministry of Agriculture, Forestry and Fisheries of Japan (http://www.maff.go.jp/eindex.html)
- Canadian Food Inspection Agency (http://inspection.gc.ca)

- Australian Quarantine and Inspection Service (AQIS) (http://www.affa.gov.au);
- Major changes to AQIS import conditions (ICON database) for AQIS (http://www.aqis.gov.au/icon32/asp/ex_alertscontent.asp)
- United States Department of Agriculture (USDA) Animal and Plant Health and Inspection Service (APHIS) (http://www.aphis.usda.gov/ppq)
- Food quality and safety (http://www.fao.org/es/ESN/index_en.stm)
- Codex Alimentarius (http://www.codexalimentarius.net/)
- Animal Health OIE (http://www.oie.int/)
- FAO Animal Health (http://apps3.fao.org/vs/index.htm)
- North American Plant Protection Organisation (http://www.nappo.org)
- New Zealand Ministry of Agriculture Biosecurity Authority (http://202.78.129.207/biosecurity)
- APHIS Part 319: Foreign Quarantine Notices that shows conditions under which products can be imported into the USA (http://www.access.gpo.gov/nara/cfr/waisidx_01/7cfr319_01.html)

The equivalent European document to the “USDA-APHIS Treatment Manual” is contained within legislation (EC) 2000/29 and (EC) 2000/36 that contains the special requirements that must be implemented by all Member States to control pests and pathogens on plants, plant products and other objects that move into and within the Member States (Anon 2000a).

The IPPC in December 2002 will consider opportunities to minimise the use of MB and ways to avoid disruption to trade in the event of further restrictions being placed on the use of this fumigant (Dr Stephen Ogden, Director Market Access Solutionz, *pers. comm*., November 2002). This follows technical consultations among Regional Plant Protection Organisations on the prospects of reduced access to MB for quarantine fumigation (Anon 2001c). The Interim Commission of the IPPC has adopted 17 International Standards for Phytosanitary Measures which endeavour to harmonise international phytosanitary practices e.g., risk analysis and risk management and non-compliance feedback. The implementation of practices consistent with these standards should result in a reduction of the QPS applications of MB. Some Parties have already capped the amount of MB that can be used for QPS purposes e.g., the European Regulation EC2037/00 that has been implemented in 15 countries. Other Parties may consider similar restrictions on the use of MB for QPS uses, though the timeframe for implementation of this restriction is unknown.

7.3 Definitions of Quarantine and Pre-shipment

In general, MB used in quarantine treatments targets quarantine pests, which are carefully defined by regulatory authorities. The treatment is officially authorised by the competent authority and not a commercial organisation and can be carried out before shipment or on arrival. In contrast, pre-shipment treatments are always carried out within 21 days of shipment and target non-quarantine pests. Pre-shipment treatments must also be authorised by the relevant authority and not a commercial organisation. The Montreal Protocol definitions of Q and PS together with an explanation of their derivations and intent follow in the following sections.

7.3.1 Definition of quarantine

Decision VII/5 of the Montreal Protocol in 1995 defined a *quarantine application* as a treatment applied to prevent the introduction, establishment and/or spread of a quarantine pest (including disease), or to ensure its official control. A *quarantine pest* is defined as a pest of potential importance to the area endangered and not yet present there, or present but not widely distributed and being officially controlled. *Official control* is that performed by, or authorised by, a national plant, animal, environmental protection or health authority.

The use of MB in a quarantine treatment can only be for pests that are officially recognised as quarantine pests. The Protocol definition of 'quarantine' is broader than the use of this term in other international plant protection conventions and treaties. However, this was regarded by the Parties as appropriate as MB is currently being used for some pest control practices such as rat control where there is a risk to human health. Human health aspects are not specifically considered in the definition of plant quarantine in other treaties and conventions.

There has been considerable discussion by the Parties on the scope of the QPS exemption. For quarantine treatments, the Parties decided to:

- Base the exemption on a narrow FAO 1994 definition of a quarantine pest, but to delete 'economic' from '…economic importance…' in the definition as there were more than just 'economic' reasons when considering 'importance';
- Restrict the exemption under quarantine to treatments carried out by government plant, health, animal, or environmental authorities; and
- Include quarantine treatments for commodities moved interstate or region within the one country.

The WTO Agreement on the Application of Sanitary and Phytosanitary Measures (the SPS Agreement) defines the basic rights and obligations of Parties with regard to the use of measures applied to protect human, animal or plant life or health, including procedures to test, diagnose, isolate, control or eradicate diseases and pests. This Agreement encourages Parties to base their national SPS measures on relevant international standards, guidelines and recommendations. Risk assessment provides the basis for measures applied in the absence of international standards.

In assessing pest risks, WTO Members are required to take into account available scientific evidence; relevant processes and production methods; relevant inspection, sampling and testing methods; prevalence of specific diseases and pests; existence of disease/pest free areas or areas of low pest prevalence; relevant ecological and environmental conditions; and quarantine or other treatment.

The Secretariat of the Food and Agricultural Organisation (FAO, IPPC), in co-operation with regional organisations operating within the framework of the IPPC, is responsible for developing international standards, guidelines and recommendations for plant health. The IPPC is recognised by the SPS Agreement as the organisation under which international standards for phytosanitary measures are established. In practice, the IPPC focuses primarily on quarantine issues.

This international agreement, although not yet ratified, is most relevant to quarantine treatments as defined by the Protocol as the IPPC promulgates guidelines for the implementation of measures for quarantine pests and regulated non-quarantine pests. However, non-regulated pests do not fall within the scope of the application of phytosanitary measures under the IPPC as they are not classified as injurious to plant health. Non-regulated non-quarantine pests are often the target of pre-shipment MB treatments, as defined under the Protocol, as they are detrimental to the *quality* of the product in which they are found.

7.3.2 Definition of pre-shipment

Decision XI/12 in 1999 defined *pre-shipment application* as a non-quarantine treatment applied within 21 days prior to export to meet the official requirements of the importing country or existing official requirements of the exporting country. *Official requirements* are those which are performed by, or authorised by, a national plant, animal, environmental, health or stored product authority.

The application of 'pre-shipment', as intended by the Parties, appears to be without a parallel in other treaties and conventions. The World Trade Organisation (WTO) Technical Barriers to Trade (TBT) Agreement aims to avoid unnecessary obstacles to trade associated with technical regulations and standards for industrial and agricultural products. The TBT applies to measures which may be used to assure *quality*. Pre-shipment treatments would generally be considered to deal with 'quality' for WTO and IPPC purposes and they would regard pre-shipment as falling under the TBT Agreement.

Unlike 'quarantine', in 1994 there was neither a definition for 'pre-shipment' under the FAO nor elsewhere. Currently, the concept of 'pre-shipment' remains peculiar to the Protocol. The Parties agreed in Decision XI/12 to a stricter definition of pre-shipment as a way of addressing concerns over potential inconsistencies in the interpretation of pre-shipment. The additional wording has helped to clarify the definition of pre-shipment:

- Only those treatments authorised by official authorities (rather than commercial-contractual agents) can be considered exempt under the Protocol;
- MB use under the exemption is to be restricted to generally one application within the 21 days prior to shipment. Previously, the date for application of MB was not specified, potentially leading to multiple applications prior to shipment;
- MB used more than 21 days before shipment is not exempt and should be recorded and reported under the controlled quota of MB in a country; and
- "Stored Product Authorities" was added to the list of authorities that officially authorise the use of MB for pre-shipment.

7.4 National Legislation on Quarantine and Pre-shipment Uses of Methyl Bromide

The European Community is the only Party to the Montreal Protocol that has placed restrictions on the quantities and use of MB for QPS and therefore it has implemented stricter control measures than is required under the Protocol.

European Union Regulation EC2037/00 that has been in force in all 15 Member States since its introduction on 1 October 2000 required a freeze on the use of MB for QPS commencing 1 January 2001 (Anon 2000). Enterprises currently placing MB on the European market for QPS purposes can place no more than the average amount of MB they placed on the market for that purpose from 1996-1998 – currently about 400 ODP tonnes in total each year.

Each year, any Member State still using MB for QPS must submit to the Commission the quantities of MB used, the purposes for which it was used and the progress being made in evaluating and using alternatives for QPS. This annual report will enable the quantity of MB authorised for QPS to be reduced in Europe in the light of technical and economic availability of alternative substances or technologies.

MB is no longer used for QPS in Denmark, Finland and Sweden; and in Austria relatively small quantities of MB are used for soil and emergency QPS applications. Denmark phased out its QPS uses by 1998 (Batchelor 2002).

Japan considered that non-QPS uses may be under-estimated because of MB licensed for QPS treatments could be used for non-QPS treatments. As a result, additional security measures in Japan for QPS uses now include labels on the cylinders to differentiate QPS from non-QPS use, shipment of QPS only to licensed fumigators, enforcement of compliance, improved pest identification to distinguish quarantine from non-quarantine pests, air tight chambers and logbooks to record volumes used by operators (Tateya 2002ab).

MBTOC was unaware of any other countries that had in place measures for restricting and labelling the amount of MB that could be used for QPS.

7.5 Quarantine and Pre-shipment Uses of Methyl Bromide

7.5.1 Reasons for quarantine and pre-shipment treatments

For those countries that export some or most of their production, perishable commodities can be a significant source of external revenue. Perishable commodities are typically kept cool after harvest in order to mimimise the impact of decay organisms which can significantly reduce their shelf-life. Their value is often enhanced by minimising the period between harvest and consumption, as their shelf life is often only a few days to several weeks; therefore rapid-acting disinfestation treatments are often very important. Durable commodities such as grain and rice are kept protected as much as possible from insects and rats in silos or bunkers and do not require such rapid disinfestation treatments.

The presence of pests in perishable commodities *post-harvest* often indicates insufficient *pre-harvest* control to comply with strict phytosanitary standards and therefore considerable attention needs to be paid to pest control before harvest. Inspection can be carried out to determine the effectiveness of the pre-harvest treatments and, if through sampling a proportion of the packed consignment the pest incidence is determined to be nil or very low, the product may be exported without a post-harvest treatment. However, field control of a pest has rarely provided quarantine security. As a general rule, 90% of the pesticide applied does not hit the target pests (Luckmann and Metcalf 1982). This results in field levels of control rarely exceeding 90% pest mortality which is an insufficient level of control for the present requirement by many countries of pests mortality greater than 99.9% for quarantine security (Baker 1939, Couey and Chew 1986).

Mangan *et al.* (1997) reported survival of Mexican fruit fly in citrus and mango, even after a quarantine treatment (previously shown to be at least 99.9968% effective) had been applied, when no pest pre-harvest management procedures were in place. Standard pest management procedures reduced predicted survival rate to less than 1 reproductive pair per shipment, which is an acceptable level of quarantine security. This work highlighted the need to maintain pre-harvest pest control measures with post-harvest quarantine treatments in order to maintain an acceptable level of quarantine security.

As a consequence of these pre-harvest pesticide application and packing procedures that follow harvest, most commodities are almost entirely free of pests when presented for export. However, complete freedom from pests is sometimes not achievable and the detection of a single pest in a consignment, when officially inspected on entry, can result in a disinfestation treatment being ordered by quarantine authorities. Generally, the disinfestation treatment applied will have been officially approved by the regulatory agency operating in each country for the commodity-pest combination, based on extensive scientific data generated to ensure a very high level of confidence in the efficacy of the treatment.

Once accidentally imported, many insect pests can have high reproduction rates if temperature and host availability are favourable. Because climate exerts such a profound influence on the distribution and abundance of insects, quantification of climate influences is of considerable interest to quarantine scientists for assessment of potential establishment and spread of exotic pests (Worner 1994). In addition, many insects in perishable commodities have short generation cycles, for example, the Oriental fruit fly produces 3-18 generations per year depending on temperature (Paull and Armstrong 1994).

Insect pests in durable commodities such as grain exist largely in an environment protected from climatic extremes or they have adapted to a wide range of climates. Under favorable temperature conditions pests can be prolific, producing, for example, in the case of the khapra beetle (*Trogoderma granarium*), around 50 offspring a generation every 6 weeks resulting theoretically in a increase to over 10 million in 6 months from one breeding pair.

It is natural for insects to be closely associated with perishable commodities because plant products approaching ripeness advertise their readiness for consumption (and seed distribution) by releasing volatile chemicals attractive to insects (Greany 1994). This association can result in insects being included in the final export package, even after the commodity is graded and checked. Bulk shipment of durable commodities such as grain and sawn timber makes commodity protection against insects difficult. The small size of the insects relative to the commodity being shipped, and the ability of insects to have life stages hidden inside the commodity, make them difficult to detect by quarantine inspectors.

As history shows, insects have become very adept at moving into new ecological niches, adapting to new conditions, multiplying rapidly and even expanding their host range. The costs of *accidentally* importing a pest can result in a significant loss of trade if the insect is a quarantine pest and exports are based on area or country freedom. Outbreaks of a pest can invoke quarantines that severely affect or eliminate harvest and transport of commodities from the infested area and buffer zone. Exotic pests can result in additional pest control or eradication costs totalling from $US5m to more than $US100m over successive years. Although fruit flies are recognised worldwide as the most important quarantine pests, there are other pests that can have similar disruptive consequences:

- A new species of mealybug, *Pseudococcus odermatti,* that is a quarantine pest has been officially described in order to distinguish it from closely related species. This species has restricted the movement of citrus from the US to Japan and from the Bahamas to the USA. It also has the potential to restrict the movement of species of ornamentals with the genus *Aglaonema* that are widely grown in subtropical areas and greenhouses (Miller and Williams 1997).

- The white peach scale, *Pseudaulacaspis pentagona,* was collected for the first time on the eastern seaboard of the island of Hawaii in September 1997. Its distribution is expected to expand rapidly, affecting the vigour of papaya trees and downgrading fruit quality as well as causing concern as a quarantine pest. A vapour heat treatment of papaya over a four-hour period that achieved a core temperature of 47.2^{o}C was considered sufficient to control the white peach scale on export shipments of Hawaiian-grown papaya (Follet and Gabbard 1999).

For these reasons, there are a large number of exotic pests are of concern to quarantine authorities in importing countries. Typically, treatments can be carried out either before export (Q or PS) or at port of entry on import. Occasionally MB might be used to control or eradicate quarantine pests that have been detected within a region or country.

7.5.1.1 Pest control - country of origin treatments

For perishable commodities, importing countries often require the exporting country to undertake a mandatory disinfestation treatment prior to export in order to control the most important pest species such as fruit flies and codling moth. For example, apples shipped to Japan from Australia (Tasmania), New Zealand, France and the United States must be treated before export to control codling moth, a pest not found in mainland Japan. MB, often combined with a period of cool storage either before or after fumigation, has been the treatment of choice. Japanese inspectors are often present in the exporting country to ensure that the treatments are carried out correctly. The treatment can only be approved after years of extensive research followed by confirmation tests in the presence of inspectors from the export country. Countries free of fruit fly such as New Zealand often require disinfestation treatments in the export country to be developed and implemented to ensure this and other serious quarantine pests are not accidentally imported in perishable commodities.

For durable food commodities, treatment before export following a strictly developed protocol as described above is rare. One example is the khapra beetle (*T. granarium*) which is a quarantine pest of grain and other durable commodities that requires a mandatory treatment in the exporting country. Some Article 5(1) Parties that export large quantities of cereal commodities are heavily dependent on fumigation with MB to satisfy their own or other countries' quarantine regulations. Several Parties, for example, export large quantities of rice, almost all of which is fumigated with MB as a pre-shipment treatment over a 24-48 hour period immediately prior to shipment. Quarantine treatments are common on timber products and packaging materials such as pallets and dunnage where serious quarantine pests such as Asian longhorn beetle have been identified. QPS treatments are carried out on stacks of bagged grain, particularly in Africa and Singapore, including food aid grain at point of import; and for the protection and disinfestation of dried fruit and nuts. Other commodities requiring QPS MB treatment for import or export include mainly tobacco, dried fish maws, seeds, cotton, logs, sawn timber, straw materials and grain. In addition, artefacts and similar objects made of organic materials that may be natural history specimens are often traded internationally and may carry pests of quarantine significance.

Quarantine treatments are often required to control specific pests, particularly the khapra beetle (*Trogoderma granarium*), the house longhorn beetle (*Hylotrupes bajulus*), the Asian longhorn beetle (*Anoplophora glabripennis*), the pine wood nematode (*Bursaphelenchus xylophilus*) and various snails. MB is still widely used on cotton in the US and elsewhere, prior to export and on import, against pink boll worm. Treatments may also be carried out on products in contact with or packed with cotton.

Based on International Maritime Organisation recommendations, MB is currently the only fumigant allowed for many quarantine treatments on ships in many countries (IMO 1996). Although MB is no longer allowed for in-transit fumigation in ship holds, but this practice still occurs. Cargo may be treated after loading and prior to sailing, either with ventilation before sailing or during the voyage. MB is also used for disinfestation of empty ships and aircraft from insects, rats and snakes.

7.5.1.2 Pest control - treatment on arrival

Perishable and durable commodities are often shipped without any disinfestation treatment prior to export and are then subject to inspection on arrival. If live pests are then detected by official inspection, most importing countries require an immediate disinfestation treatment 'on entry' or the commodity is ordered to be reshipped or destroyed.

'On entry' treatment to control quarantine pests remains one of the most important areas where substitution of MB will be technically difficult. Ideally, alternatives that replace MB for 'on entry' applications should be of short duration and capable of being carried out on-site or only in proscribed ports. Many of the disinfestation treatments developed so far have not been found suitable for rapid ship-side treatment of a large range of perishable commodities.

In Europe there are now commercial treatments for controlling non-quarantine pests in durable commodities based on controlled atmosphere fumigation (for further information, see Section 7.7.1.6 and www.ecogen.nl).

7.5.2 Consumption of MB for Quarantine and Pre-shipment

TEAP reported previously that about 22% of the global MB consumption was used for QPS purposes, and that for some Parties, QPS consumption was increasing (TEAP 1999). A number of Parties in 1999 expressed concern that MB consumed for QPS was now much greater than when the exemption was originally agreed in 1992. In the light of these concerns, the Parties agreed in Decision XI/12 to mandatory rather than voluntary reporting of QPS consumption to the Ozone Secretariat.

MBTOC reported the potential for inconsistency in the interpretation of the terms ‘quarantine’ and ‘pre-shipment’ which has led to inaccuracy in the data reporting for QPS by Parties (TEAP 1999). For example, MB treatments of commodities that were required contractually, rather than officially, would not qualify as QPS but some Parties appeared to include this use in their reported total of exempt MB consumption. This inconsistency resulted in an understatement of a Party’s calculated annual controlled consumption, i.e. non-QPS uses, in a particular year. To assist the Parties in the interpretation of ‘quarantine’ and ‘pre-shipment’, MBTOC designed a QPS Logic Diagram (TEAP April 1999) which has subsequently been modified to take account of changes to the definition of ‘pre-shipment’ agreed by the Parties in December 1999 (UNEP-TIE 2002). This Logic Diagram could be used as the basis for designing national survey forms to accurately monitor, record and quantify QPS consumption. Mandatory reporting of QPS, combined with accurate differentiation of MB used for ‘quarantine’ or ‘pre-shipment’, will assist the Parties in determining the consumption of MB for QPS in the future.

MBTOC employed several different methods in estimating the volume of MB used for QPS. There is broad agreement in the production-based and consumption-based estimates. The Ozone Secretariat data shows that more than 11,410 tonnes MB was produced for QPS in 1999, while other estimates indicate that production for QPS may have been about 11,825 tonnes. Production information available to date for 2000 indicates a range of about 10,475 – 11,800 tonnes MB production for QPS purposes, accounting for about 19 - 21% of fumigant production (Section 3.4.3). Table 7.1 indicates an estimated range of about 10,600 - 12,300 tonnes for QPS, calculated on sectoral consumption estimates. With this method of estimation, QPS accounts for about 19 - 22% of global consumption in 2000.

Table 7.1 Estimate of the proportion of MB used for QPS in 2000, based on sectoral consumption calculations

Sector	Estimated QPS range (metric tonnes)	
	Low estimate	High estimate
Durables	2,151	3,441
Timber, pallets, packaging	3,895	4,104

Structural	28	43
Perishables	4,571	4,715
Total	**10,645**	**12,303**
Percent global consumption	19 %	22 %

Under Decision XI/12, the Parties requested TEAP to report in 2003 on the technical and economic feasibility of alternative treatments for QPS and to provide an estimate of the volume of MB that would be replaced by the implementation of alternative, non-MB QPS treatments. Under this same Decision, Parties were also:

- Urged to review their national plant, animal, environmental, health and stored product regulations with a view to remove the requirement for the use of MB for QPS where technically and economically feasible alternatives exist. This action is particularly relevant for pre-shipment treatments where MBTOC (1998) reported a range of alternatives;
- Urged to implement national procedures to monitor the use of MB by commodity and quantity in order to target efficiently the use of research resources for developing alternatives for QPS; and
- Encouraged to implement recovery and recycling technology for QPS when technically and economically feasible in order to reduce emissions until such time that alternatives to QPS are available.

MBTOC will therefore undertake a survey of MB used for QPS for submission to TEAP for its report to the Parties in 2003. Further data collection is required in order to assess the volume and uses of MB under QPS, the extent of the development of alternatives, the likely operation of exemptions in the future once MB is phased out and the regulations governing the use of QPS treatments.

7.6 Constraints limiting the development of alternatives for quarantine and pre-shipment

MB has been, and still is, the treatment of choice for perishable and durable commodities that require treatment on arrival and for the past 40 years there has been little need to consider alternatives to MB for these uses. The almost universal application and acceptance of MB for post-harvest disinfestation has stifled the search for alternative treatments.

Quarantine treatments applied on arrival for perishable commodities are a special case-in- point. They must be fast-acting to minimise the risk of a quarantine pest escaping and to avoid handling delays which lead to spoilage of the product. The regulatory authority usually does not allow significant movement of the commodity away from the vessel, or will only allow movement to a treatment facility located at an approved port of entry. Many imported consignments such as apples, grapes and bananas arrive as very large consignments, typically occupying the entire cargo ship. Compared with physical treatments that use heat or cold to kill pests, chemical treatments are much faster acting, relatively easy to apply and offer the best prospect for rapid disinfestation with minimal disruption to port facilities. However, registration of a new chemical for food uses is costly, time-consuming and has a high chance of failure – risks that many chemical companies are not willing to take.

The constraints outlined above and others that limit the development of alternatives are discussed in the following sections: research funding (Section 7.6.1); adherence to strict scientific standards when undertaking research to demonstrate treatment efficacy without reduction in commodity marketability (Section 7.6.2); equipment development and implementation of large-scale insect rearing programmes (Section 7.6.3); phytotoxicity testing (Section 7.6.4); economic, logistical, environmental, regulatory and engineering considerations affecting commercialisation of any proposed treatment (Section 7.6.5); and opportunities to substitute the use of MB with alternatives in pre-shipment treatments (Section 7.6.6).

7.6.1 Research funding

The current exemption for MB for QPS uses under the Montreal Protocol results in a lower priority for research on QPS alternatives than uses such as soil treatments where consumption under the Protocol is controlled. For soil treatments, the need to ensure that alternatives are in place in developed countries by 2005 is widely recognised as urgent. As a result, research laboratories involved in postharvest disinfestation of perishable commodities - and durable commodities that have QPS requirements - report continued difficulty in securing funds to continue research on the development of postharvest treatments that will substitute for MB.

About 30% of the MB in the United States is used for postharvest and structural treatments, mostly to meet phytosanitary standards for international trade (Dowdy 2002). The United States Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine (USDA, APHIS, PPQ) supports the continued use of MB for QPS treatments as exempted under the Montreal Protocol. However, the agency justifies research expenditure to find alternatives despite the exemption as it believes it is important to develop and adapt alternative technologies that can lead to reduced gas emissions and overall use.

7.6.2 Scientific standards

The development of new treatments for perishable commodities is generally time-consuming as each treatment must meet strict scientific standards demanded by the regulatory authority from the importing country. For example, most regulatory agencies have a policy of only accepting 99.9968% mortality (called Probit 9, Baker 1939). Due to the adherence to strict scientific standards, quarantine treatments typically require 3-7 years to complete the technical requirements. Possibly 10 or more years are needed if an entirely new quarantine treatment is to be developed. This period could be longer if specialised equipment must be designed and built before research can commence.

Regulatory authorities may require a treatment to be tested prior to approval even if the treatment is in current use in another country. This ensures that no assumptions have been made on the effects of the treatment on pest efficacy and commodity quality as for example, pest and commodity responses to the treatment may vary between regions and countries. Most countries will also not accept an alternative for a specific commodity until the treatment efficacy is proven for each commodity-pest combination. Post-entry alternative treatments used by the importing country are particularly problematical because many alternatives have neither been approved for treating a specific product on arrival, nor would they be easy to implement. To solve this problem, a range of officially approved alternatives is urgently needed to cope with a large and highly varied volume of produce entering via multiple air and sea ports. Such treatments would need to be able to treat perishable commodities quickly in order to avoid congestion at busy ports and loss of products. Government approval by the importing country often requires extensive technical documentation, which is often the major impediment to final approval of quarantine treatments.

Some scientists have suggested that Probit 9 mortality may not be necessary to achieve quarantine security as it may be too severe, impractical and unnecessary for commodities that are rarely or poorly infested (Landolt *et al.* 1984, Baker *et al.* 1990, Vail *et al.* 1993; Liquido *et al.* 1996). For some agencies, the use of Probit 9 security may be based largely on policy considerations rather than technical justification. Delegates to the December 1993 CODEX meeting supported Pest Risk Analysis (PRA) as a method for making phytosanitary decisions (CODEX 1993). Some regulatory agencies have now accepted lower levels of mortality based on pest risk analysis (PRA) methodology (Heather 1994a). Harte *et al.* (1992) developed a probability model to quantify the quarantine risk from importing fruit fly hosts, based on pre-determined and known infestation levels in the host, lot size imported and the tolerance level permitted. An alternative approach that has been proposed is to measure the risk as the probability of survival of one or more reproductive units in a shipment. Recently, the Food and Agricultural Organisation (FAO) International Plant Protection Convention (IPPC) has developed 'Principles of Plant Quarantine as related to International Trade' which seeks to harmonise quarantine policies between countries and these principles will influence the development and use of alternative treatments in the future.

In order to avoid loss of exports or restriction on imports due to the unavailability of a commercial alternative to MB, treatment acceptance criteria for new treatments are under review by scientists, industry and regulatory agencies in an effort to streamline the process of developing and implementing alternatives as rapidly as possible. USDA-APHIS continues to improve regulatory requirements and review procedures to allow treatments to become available as quickly as possible (Griffin 1996).

Alternative treatments are developed and implemented by integrating many technical, environmental and regulatory factors. Mamat and Husain (1994) have proposed a standard quarantine treatment protocol design to be considered by researchers when embarking on a treatment that will be evaluated by a regulatory agency. A useful summary of the regulatory factors affecting international trade has been provided by Ganapathi (1994) in which harmonisation of phytosanitary principles, plant quarantine procedures and pest risk assessment are discussed. Shannon (1994) also discusses the principles of international trade and outlines the system of pest risk analysis used by the United States Animal and Plant Health Inspection Service (US-APHIS). The Japan Plant Quarantine Association has published the theory and practice of fumigation and thermal disinfestation techniques, including procedures for undertaking and confirming treatments (Anon 2002e).

7.6.3 Equipment development and mass rearing of test insects

There may be a need to design, develop and build sophisticated equipment, particularly if combination treatments which inevitably leads to delays in the start of experiments. Neven (1994a) and Petry and McDonald (1995) reported on the construction of experimental equipment capable of delivering heated, controlled atmospheres (CAs) uniformly distributed throughout a chamber. This equipment was constructed to test the insecticidal nature of heated CA treatments on codling moth in apples and cherries and their impact on fruit quality.

Often development of a quarantine treatment depends also on developing procedures to mass rear the test species as a year-round supply of thousands of insects of a precise age may be required (Carpenter *et al.* 1995b).

7.6.4 Phytotoxicity testing

There is often very little treatment differential between killing the pest and not damaging the commodity. Phytotoxic responses by plant tissues are influenced by a number of factors including the treatment duration, the type of treatment, its concentration, its physical range (moderate versus high temperature) pre-harvest handling, post-harvest treatments and the innate resistance of the commodity. In general, low temperatures less than 10-12°C for tropical commodities and less than 7°C for subtropical commodities cannot be used for disinfestation treatments (Paull and McDonald 1994). To make treatment development and implementation even more difficult, commodities often vary in response from variety to variety and there may even be seasonal differences in response within a variety (Houck and Jenner 1997).

New alternative treatments are generally more pest and commodity specific than MB. Few have all the attributes of the ideal disinfestation treatment. In order to minimise any detrimental effects on the quality and market life of perishable commodities, treatments implemented commercially are typically of short duration. Modification of post-harvest handling and packing may be required. The physiological responses of horticultural produce to a range of physical insect disinfestation treatments including irradiation, heat, cold, controlled atmospheres, reduced pressure and washing has been reviewed by Paull (1994).

7.6.5 Commercialisation

Once the research supporting a treatment is approved as efficacious, economic, logistical and engineering considerations govern the commercialisation of the proposed disinfestation treatment. If an alternative treatment to MB is to be adopted by industry, it must also be practical to apply and capable of being documented to prove that the treatment has been carried out satisfactorily. Adequate monitoring and verification are needed to ensure that treatments are efficacious and properly applied. The use of heat, cold and irradiation require closer attention for proper treatment than MB because pests, although sterilized or otherwise controlled, may not be dead after application and a treatment failure may not be recognized until a commodity is widely distributed (Dowdy 2002). The treatment must also be cost effective (determined mainly by equipment and operating costs) and result in an acceptable level of residues. Additional effort may be needed in crop production, such as the effective use of integrated pest management and systems approaches, to minimize the number of pests present in a commodity at harvest. Such practices will reduce the number of pests challenged by a treatment while maintaining or enhancing commodity quality.

7.6.6 Opportunities for alternatives for pre-shipment treatments

There is a greater opportunity to implement alternatives for pre-shipment treatment than quarantine treatments as pre-shipment treatments target non-quarantine pests rather than quarantine pests and the scientific data requirements might not be as stringent to support the high level of efficacy for the alternative. However, to implement such pre-shipment treatments may require agreement from the exporting or importing country that an alternative will substitute for MB, and that there may need to be changes to handling and storage practices in order to implement the alternative. The development of alternatives for MB in pre-shipment treatments is underway in a number of countries such as Malaysia for rice treatments, and in Europe, where alternatives have replaced MB for many durable commodity fumigations, Ecogen Ltd in Holland (www.ecogen.nl) has commercialised the use of inert atmospheres to control pests in imported tobacco products, cocoa beans, rice, cereals, grains, nuts, peanuts, pulses, seeds and spices, as well as furniture and artefacts.

7.7 Alternatives to Methyl Bromide

This section describes thirteen categories (e.g. heat, cold, irradiation) of existing or potential alternatives to MB for QPS for perishable and durable commodities. While not all treatments listed as existing have replaced MB use in the past, most are considered candidate treatments that could replace MB in the future.

There are a number of relevant references that provide a useful overview of treatments for perishable and durable products. Cox (1997) provided a general overview of post-harvest treatments with particular reference to their effect on consumer acceptability. Johnson and Heather (1994) provide a review of post-harvest disease and pest control in tropical fruit, including a useful outline of the steps required for approval by quarantine agencies when developing treatments based on chemical and non-chemical methods. Hallman and Quinlan (1996) summarised the key issues and challenges facing post-harvest quarantine treatment research. Aluja (1996) argued that integration of alternative 'biorational' fruit fly management strategies would result in better management of fruit flies than alternatives that rely on just one or two strategies.

7.7.1 Principal alternatives to methyl bromide

The principal cultural, non-chemical and chemical alternatives to MB are discussed in this section, followed by their application to specific key perishable and durable commodities.

7.7.1.1 Cultural practices leading to pest reduction

The 'Systems Approach' as applied to perishable commodities is the implementation of multiple safeguard actions in the country of export that result in a commodity meeting the phytosanitary standards of the importing country (Shannon 1994). These actions have a scientifically derived basis and can be quantified at key points in the production-to-export system (hence the term 'Systems Approach'). The Systems Approach to achieving quarantine security is described in detail by Jang and Moffitt (1994).

Sometimes the Systems Approach is also ascribed to durable commodities and in this case refers to actions taken after harvest to minimise pest incursions in stored products.

The Systems Approach includes the following steps: (1) consistent and effective management for reducing pest populations in the field and monitoring this management; (2) prevention of contamination after harvest; (3) culling in the packhouse; (4) inspection and certification of the critical parts of the system based on effective trace-back procedures; and (5) shipping using methods that prevent re-infestation. The Systems Approach is highly dependent on knowledge of the pest-host biology and phenology. Using pest risk analyses, the probability of accidentally exporting the pest is often shown to be minimal and in some cases exceeds the level of quarantine security achieved by fumigation alone (Moffitt 1990). Provided there is no pest breeding in storage, the Systems Approach can achieve or exceed the level of quarantine security acceptable to an importing country and in some situations, without any further actions needed (Vail *et al.* 1993). Whiting (1995) proposed integrating pre- and post-harvest pest control practices to reduce the incidence and viability of quarantine pests on export commodities.

Reduction in insect populations can be achieved by cultural practices such as: planting crops that are no longer the preferred host of the insect (host plant resistance); harvesting when the commodity is not susceptible to attack (e.g. papaya which is harvested immature and ripened later); harvesting when the pest is not active (e.g. when the pest is in diapause or over-wintering stage of the pest); improved harvesting practices that remove 'hitchhiker pests' in the field or orchard; the addition of biological agents such as parasitoids and predators; releasing sterile insects; using pheromones; using microbial agents as pest pathogens; or as practiced in some Asian countries by wrapping crops such as pears, apples and peaches on the tree with pesticide-impregnated paper. However, in some cases the presence of biological and microbial agents on the commodity after harvest may cause quarantine concern which is a limitation on the widespread use of this form of pest control.

Commodity resistance to pest attack has allowed many commodities to enter trade without the need for a quarantine treatment. Drawing on mainly tropical commodities as examples, commodity resistance based on known susceptibility to pests, cultivar variability, stage of maturity and growing periods has been summarised by Armstrong (1994a). For example, Hennessey *et al.* (1992) found no Caribbean fruit fly (CFF) infestations in more than 100,000 Tahiti limes collected and examined from 184 groves in Florida over 60 harvest dates, effectively presenting a case for no disinfestation treatment required for this pest/commodity. Grapefruit also increase their oil content in the skin which results in resistance to CFF attack. This oil increase is correlated with a colour change which, in the future, may allow skin colour to be used as an indicator of shipments free of this pest (Greany 1994).

The Systems Approach for control of major quarantine pests often exceeds the security level required by some countries and could become more prevalent as a substitute for MB in the future. However, inter-governmental agreements accepting the Systems Approach as a disinfestation treatment are rare because the pre- and post-harvest measures are time-consuming to establish and document, and difficult to regulate. Commercially, there are few examples:

- Japan accepts a Systems Approach for citrus exported from Florida (Anon 1990a);
- Brazil accepts a Systems Approach for apples exported from the United States (J. Thaw, USDA-APHIS, pers. comm. 1997);
- The USA accepts avocados exported from Mexico to 19 Northeastern states in the USA that are certified free of avocado seed weevil, avocado seed moth, avocado stem weevil, fruit fly and other hitchhikers based on field surveys, trapping and field treatments, field sanitation, host resistance, post-harvest safeguards (e.g. tarpaulins on trucks, screened packhouses) packhouse inspection and fruit cutting, winter shipping only and port of arrival inspection (Firko 1995; Miller *et al.* 1995).

7.7.1.2 Pest-free zones and periods

A pest-free zone is the establishment of a certified area where a regulated quarantine pest does not exist, even though it may be established in another area within the same country (Shannon 1994). Based on survey technology and data that confirm the area is free of the organism of concern, the exporting country establishes formal, specific regulatory measures to protect the area and an ongoing surveillance system that ensures early detection of any infestations in the area. These systems are dependent on scientific information, judgements about organisms behaviour and survey technologies and methods.

Pest-free zones have been established by many countries and consist of geographic areas where commodities may be produced and exported because of the absence of pests of quarantine importance. For example, Japan accepts: melons from the Hsingchang Uighur Autonomous Region in China based on this area being a melon fly free zone (Anon 1988a); capsicum, egg plant and tomatoes produced in Tasmania (Australia) as free from Tobacco Blue Mold *Peronospora tabacina* (Anon 1996a), Mediterranean fruit fly (Mediterranean fruit fly, *C. capitata*) and Queensland fruit fly (*Bactrocera tryoni*) (Anon 1989a); strawberry, cucumber, pepper, tomato, egg plant, grapes, squash and melon from the Netherlands as free of Mediterranean fruit fly (Anon 1993a); and grapes, kiwifruit and other produce from southern Chile as free from Mediterranean fruit fly (Anon 1996b). In the future, it may also be possible to establish pest-free periods provided quarantine authorities can be assured of times during the growing season when it is not possible for the pest to infest the commodity. Further examples of pest-free zones are provided by Riherd *et al.* (1994).

An advantage of the Pest-free Zone is that no treatment need be applied post-harvest and therefore marketability of the commodity is not reduced, which is sometimes the case when a disinfestation treatment is applied (including MB treatments). However, these zones are often restricted to geographically isolated areas with buffer zones that exclude host plants and residential areas where possible, require continuous enforcement, monitoring and reporting, are based on extensive knowledge of the pest and commodity biology and are generally expensive because of all these factors.

7.7.1.3 Inspection and certification

Some countries inspect a sample of the produce prior to export (termed pre-shipment inspection) and certify each consignment based on levels of acceptability for pests of quarantine importance. For example, Japanese quarantine officials inspect cut flowers in the Netherlands and Colombia which reduces the need for inspection and disinfestation on arrival in Japan. However, this usually does not preclude further inspection on arrival. Some commodities are accepted only after inspection of the packed commodity and endorsement of the procedures used by the importing country to kill any live pests (e.g. Japan, United States, New Zealand) or that live pests are within permissible limits (e.g. New Zealand) (Baker *et al.* 1990).

Inspection is labour intensive. The costs of inspection are typically borne by growers and packers in the exporting country for pre-shipment certification and by the government from the importing country for inspection on arrival. These costs may be reduced in the future using automatic inspection systems under development such as low-dose X-rays to 'see' pests, or detection systems to 'smell pests' when they release pest-specific chemicals.

7.7.1.4 Non-chemical postharvest treatments

Non-chemical alternative treatments to MB are generally environmentally sound and leave commodities free of chemical residues. However, compared with MB fumigation, they can require more technical expertise in their development, implementation and operation in order to kill pests without damaging the commodity. They are also generally effective in controlling a more limited range of pests than MB (Kawakami *et al.* 1998).

Those treatments used commercially, or with potential for commercial use in the near future, are discussed first. Few have been accepted for quarantine use. Heat and cold dominate those non-chemical alternatives commercialised to date and extensive research is needed in most cases to commercialise other non-chemical treatments.

7.7.1.5 Cold

Cold storage can be used as a quarantine treatment to ship perishable commodities to areas where the fruit would otherwise not be permitted. It is most useful as a treatment when it is used as part of the normal handling, distribution and marketing procedures. Cold treatments cannot be applied to commodities that exhibit cold injury, a physiological disorder that affects many tropical commodities.

Cold treatment is generally applied to fruit potentially infested with tropical pests, which have relatively little tolerance to cold conditions compared to temperate pests. The temperature range acceptable for the use of cold treatment is typically very narrow and in addition the treatment must be documented in detail to satisfy the importing authorities.

The duration and temperature of the treatment (typically -1°C to +2°C) depend on pest susceptibility and fruit tolerance to cold conditions. Pest mortality can vary with previous temperature exposure. For example, Phillips *et al.* (1997) reported that the mortality of Mediterranean fruit fly in litchi is lower than for carambola when exposed to the same temperature regime suggesting that host fruit may influence the mortality of fruit flies exposed to cold treatments.

Cold treatment is particularly suitable for controlling pests found in or on some subtropical (e.g. citrus) and tropical (e.g. mangosteen) commodities provided a treatment period, usually of at least 10 days, can be accurately maintained and documented. Cold treatment is carried out in-transit or in land-based facilities. Some chilling damage can occur during treatment for some chilling-sensitive commodities. Chilling injury can be reduced if the commodity is conditioned to relatively low temperatures prior to cold storage (Houck *et al.* 1990b).

Cold treatment is approved for use as a quarantine treatment in at least 55 countries that export perishable commodities mainly to Japan and the United States including Albania, Algeria, Argentina, Australia, Belize, Bermuda, Bolivia, Bosnia and Herzegovina, Brazil, Chile, China, Colombia, Costa Rica, Croatia, Cyprus, Dominican Republic, Ecuador, Egypt, El Salvador, France, Greece, Guatemala, Guyana, Haiti, Honduras, Hungary, India, Israel, Italy, Japan, Jordan, Lebanon, Libya, Macedonia, Mexico, Morocco, Nicaragua, Panama, Peru, Philippines, Portugal, South Africa, Spain, Suriname, Swaziland, Syria, Taiwan, The Netherlands, Trinidad and Tobago, Tunisia, Turkey, Uruguay, USA, Venezuela and Zimbabwe. As examples, Japan accepts coolstorage conditions as a quarantine treatment for four species of fruit flies (Mediterranean, Queensland, oriental and melon fruit flies) potentially infesting grapes, kiwifruit and citrus from Australia, Chile, China, Hawaii, Israel, Philippines, South Africa, Spain, Swaziland and Taiwan (Kawakami 1996).

Low temperature treatments conducted in-transit are not as limited by the time requirements needed for control and have been effective for many years (Dowdy 2002). Recent failures of low temperature in-transit treatments, however, have resulted in a re-evaluation of the treatment with an emphasis on adequate distribution of the treatment temperature throughout the container or ship hold. As a result of problems in the efficacy of the cold treatment on Clementine oranges imported from Spain, APHIS recently amended its PPQ requirements for Mediterranean fruit fly (*Ceratitis capitata*), melon fly and oriental fruit fly (Bookout 2002). In general, cold treatments will be no less than 14 days and at temperatures no more than 1°C. On average, this will add 2 days to the treatment time. In addition USDA inspections on arrival will increase and will include examining the interior of some of the fruit in the consignment.

A summary of the uses of cold treatment and further examples has been provided by Gould (1994). For cold treatments identified by MBTOC for a range of perishable commodities, see Section 7.10.

7.7.1.6 Controlled atmospheres (CAs)

Fruit shelf-life can be extended by altering the normal atmosphere of 21% oxygen and 0.03% carbon dioxide to about 0.5 - 3% oxygen and 2 - 5% carbon dioxide and controlling it at these levels. Typically the treatments are carried out at optimum storage temperatures and times for the commodity which may be too short for acceptance as a quarantine treatment. Although CAs have been widely used for at least 30 years for prolonging the storage life of apples and pears, there are few commercial uses of CA for disinfestation of fresh products because lengthy periods in standard CA cool storage are required to achieve high pest mortality which can result in an unacceptable reduction in commodity quality (Meheriuk and Gaunce 1994). The use of CAs in the trade of perishable commodities has been summarised by Carpenter and Potter (1994).

CA is particularly suitable for controlling some pests on perishable products that store well such as apples (Batchelor *et al.* 1985, Whiting *et al.* 1991 for control of Lepidoptera under low and high temperature CA, Dickler 1975 for low temperature control of scale insects).

Commodities show great varibility in their ability to tolerate CAs which limits the development of a generalised CA treatment. Vegetables tolerate a minimum of 0.5% oxygen; some cultivars of apples and pears, broccoli, mushroom, garlic, onion 1%; most cultivars of apples and pears, kiwifruit, apricot, cherry, nectarine, peach, plum, strawberry, pineapple, olive, cantaloupe, sweetcorn, green bean, celery, lettuce, cabbage, cauliflower and Brussels sprouts 2%; avocado, persimmons, tomato, pepper, cucumber, artichoke 4%; citrus, green peas, asparagus, potato 5% (Kader and Ke 1994). Carbon dioxide maximum tolerance shows similar variation by commodity from 2% to 15%. Most commodities exhibit low oxygen and/or high CO_2 injury and off-flavour development when exposed to insecticidal CA conditions outside of their tolerance range (Kader and Ke 1994) that limits the successful use of CA treatments for disinfestation to relatively few perishable commodities. In addition, insect pests can often survive low oxygen conditions for long periods, particularly at low temperatures.

More recently CAs have proven effective on a laboratory scale for quarantine control of temperate and tropical pests (not tested inside the commodity) particularly when combined for short durations with temperatures above 30°C (Whiting *et al.* 1991, Jessup 1995). Unfortunately, in some cases the requirements for insect control damage the commodity (Smilanick and Fouse 1989). CA treatment alone is not known to be approved for quarantine use by any country (Anon 1998b).

Other factors limiting widespread adoption of this technology are inadequate data on the responses of pests and commodities to high-temperature CA, the difficulty of designing large high-temperature CA disinfestation facilities with adequate gas retention and regional variation in the cost of gases for CA (Whiting *et al*. 1991; Benshoter 1987). Carpenter *et al.* (1995ab) reported that the problems likely to be associated with the implementation of CA treatments at elevated temperatures (60% CO_2 + 40% N_2 at 35°C for 2, 4, or 8 hours) were variability in produce and pest responses and the limited ability to extrapolate laboratory data to commercial conditions for a variety of pests and produce.

Treatment with *controlled atmospheres*, based on carbon dioxide or nitrogen, offers an alternative to fumigation for insect pest control, but not fungal pests. Controlled atmospheres are unlikely to be used where fast turn-around is necessary, unless the technique is combined with such measures as high pressure or raised temperature. Cold treatments are now used as part of IPM systems for stored products and artifacts. Heating can also synergise the effects of other treatments, for example fumigants, controlled atmospheres and inert dusts.

Ecogen Ltd in Holland (www.ecogen.nl) has commercialised the use of inert atmospheres (low oxygen, high carbon dioxide) at 18-25 ºC as a postharvest treatment to control pests in 3-9 days in a wide range of durable commodities such as tobacco products, cocoa beans, rice, cereals, grains, nuts, peanuts, pulses, seeds and spices, as well as furniture and artefacts. The inert atmospheres are generated by burning propane or methane, and the cost of the treatment is similar to MB fumigation. This system is used commercially in the port of Rotterdam where 36 chambers sited in various warehouses have the capacity to treat about 80,000 tonnes per year. Additional capacity is under construction to allow the treatment of freight containers.

Treatments are also carried out in barges, bakeries, factories, warehouses, silos, vehicles, museums and aircraft. Ecogen uses high levels of CO_2 for up to 12 hours as a replacement for MB for killing vertebrate pests in aircraft.

Controlled atmospheres have the potential for use in wood products but long exposure times are required for treatment at ambient temperatures. The efficacy of controlled atmospheres at elevated temperatures for treatment of logs for export is being studied in New Zealand (Dentener *et al.* 1997).

7.7.1.7 Heat

Heat is particularly suitable for controlling pests found in or on most tropical and some subtropical commodities. Costs of heat treatment were reported as 6 - 7 times more expensive than MB fumigation (US-EPA Case Study December 1996). Recent increases in the cost of MB have probably made heat treatments more cost-competitive with MB. The temperature, duration and application method must be sufficiently precise to kill pests and not reduce the marketability of the commodity. However, heat is unsuitable for many highly perishable products such as asparagus, some stonefruit (cherries in particular) and leafy vegetables as their shelf-life and marketability is significantly reduced by the treatment. Currently heat treatment facilities capable of handling large volumes of commodities are limited in size and number and limited data are available for regulatory approval of any commodity-heat-pest combination – both conditions that currently limit the more widespread application of this treatment.

Numerous heat schedules have been published by USDA-APHIS attesting to its value as a disinfestation treatment for viruses, nematodes, insects, mites, fungi, bacteria and snails. Summaries describing the quarantine uses of heated water and air have been produced (Sharp 1994 for hot water treatments, Hallman and Armstrong 1994 for heated air treatments).

Heat treatment facilities have been installed in commercial packing houses on Hawaii, Kauai, Molokai and Oahu islands in Hawaii (Lawrence 2001). Other facilities have been constructed in Australia, Fiji, Tonga, the Cook Islands and New Caledonia (Armstrong *et al.* 1998; Waddell *et al.* 1997a; Waddell *et al.* 1997b).

Heat treatments include those using moist (>90% relative humidity (r.h.) also called 'vapour heat') or dry air (<90% r.h.) and immersion in hot water (Armstrong 1994b, Paull and McDonald 1994). In general, heat treatments are carried out for 10 minutes to eight hours (Anon 2002f) at temperatures that range from 40 - 50°C depending on the specific temperature and duration known to be lethal to the pest. For more heat-sensitive commodities, it may only be possible to control surface pests.

Commercial shipments of tropical fruit such as mango are immersed in warm water at 46.1°C and above for 65 - 90 minutes to kill any pests that might be present (Anon 2000f). The water temperature and immersion period in this quarantine treatment are precisely maintained so that the pest tolerance to heat is exceeded without damaging the commodity. Papaya exposed to fruit centre temperatures of 47.2°C is commercially shipped from Hawaii to the mainland USA after 4 - 7 hours dry-heat (Armstrong *et al.* 1989) or to Japan after the same exposure time to *vapour heat* (Anon 1972). This treatment kills all stages of 3 species of fruit fly potentially infesting this commodity. Laboratory tests are being conducted to determine the potential of water dips and vapour heat treatments to kill temperate pests associated with apples, stonefruit, kiwifruit and citrus, and the effect of these treatments on their storage life.

Vapour heat is used commercially for control of oriental, melon, Queensland and Mediterranean fruit flies potentially infesting litchi, papaya and mango exports from Australia, China, Hawaii, Philippines, Taiwan and Thailand to Japan (Kawakami 1996); as a quarantine treatment for oriental fruit fly potentially infesting papaya, mango and sweet pepper; for melon fly potentially infesting netted melon and bitter cucumber; and for sweet potato weevil, west Indian potato weevil and sweet potato vine borer potentially infesting Japanese sweet potatoes shipped to the mainland from the southern islands of Japan (Kawakami 1996).

Pest control using heat generated from microwave technology is in the early stages of investigation. Microwave technologies and applications currently used by the military may eventually find use as quarantine treatments (Armstrong 1994b). Microwaves may be useful to control pests that are in the seed of commodities such as mango and avocado.

Sharp (1996) reported that increasing microwave power reduced the time to reach the target temperature but reduced the efficacy of the treatment in controlling Caribbean fruit fly larvae. Microwave technology may also allow on-site treatment of commodities which could be advantageous for quarantine treatment of small shipments. Further research is required to determine the potential of microwaves to kill pests without reducing commodity quality.

Microwave technology has recently been reported as effective in controlling *Tilletia indica* teliospores (Karnal bunt of wheat) in 10 seconds compared to 96 hours using MB (Ingemanson 1997). The author speculated that this technology that uses specific infrared species targeted at the molecular level could be used for disinfestation of pests in fruits and vegetables.

Hallman and Mangan (1997) described a number of problems with quarantine treatment research based on temperature that should be considered by researchers. These problems were the methods and criteria used to assess pest mortality after treatment, potential differences in heat tolerance between laboratory and wild insects of the same species, temperature profiles achieved commercially compared to those tested, variability in the commodity that allows for survival of the pest and the ability of laboratory conditions to simulate those used commercially.

Certain cut flowers were more susceptible to heat injury during cool, rainy seasons (Hara 1997). Conditioning flowers in hot air at 39 - 40°C for 2 - 4 h before hot water treatment eliminated seasonal phytotoxicity, but increased survival of mealybug cut flower pests. The increase in tolerance to heat by pests induced by a conditioning treatment needs to be carefully evaluated prior to commercialisation of the disinfestation treatment.

Houck and Jenner (1997) showed that, using a number of controlled-temperature glass houses, the pre-harvest environment affected the response of lemon fruit to cold, heat and fumigation treatments. Fruit preconditioned on the tree to cool temperatures were tolerant after harvest to cold treatment, but not heat, and the converse was true for lemons grown in a warm environment. Therefore the environment in which the fruit was grown is one of the factors that determines the type of disinfestation treatment that could be successfully applied.

Heat-based treatments for disinfestation of perishable commodities have been reviewed (Anon 1996c). A more specific review of potential controls for *Anastrepha* species of fruit flies describes a number of heat-based treatments as well as those using irradiation, refrigeration, modified atmospheres and combinations of these treatments (Wolfenbarger 1995a).

Heat treatment technologies are notable as one of the very few pest control options that are capable of matching the speed of treatment afforded by MB and other fast-acting fumigants. The time required is strongly dependent on the temperature reached and experienced by the target pest. Heat treatments are used to disinfest wood products either by kiln drying or application of steam heat to bulk shipments or to dunnage. Several countries have approved certification procedures for kiln drying for solid wood packaging materials against Asian longhorn beetle (Canadian Food Inspection Agency 2001; Nam *et al.* 2001) and there is also an international standard which permits the use of MB or heat or a systems approach for meeting quarantine standards (NAPPO 2002).

Dry heat treatment could also be a QPS alternative for small quantities of logs. Heat treatments (steam or hot water dips) developed for control of fungi should give complete disinfestation from insects, mites and snails. Steam heat or hot water dips are generally most suitable, but kiln drying or dry heat is suitable for sawn timber. Pine wood nematode *Bursaphelenchus xylophilus* was controlled in pine exposed for 30-60 minutes at 56 ºC in a vapour heat treatment in Japan (Kawakami pers. comm. 2002). Heat treatment by steam has been shown to eradicate all fungi tested when 66^{o}C is held at the centre of wood for 1.25 hours (Miric and Willeitner 1990, Chidester 1991, Newbill and Morrell 1991).

In practice few heat treatment schedules have been approved in the US for perishable commodities as approval depends on *in situ* pest/fruit trials, precisely controlled temperatures to avoid commodity damage, and compliance with regulatory treatment criteria and equipment certification. Development of these schedules is therefore largely empirical, costly and time-consuming resulting in the commercialisation of relatively few heat-based quarantine treatments.

To expedite the development of cost-effective treatment schedules, an international thermotolerance database, based on standardised testing procedures and analysis methods, has been proposed (Hansen and Sharp 1997, Lay-Yee *et al.* 1998, Shellie 1998, Thomas and Shellie 1998, Whiting and Hoy 1998, Jang *et al.* 1999, Mangan and Shellie 1999). Once such a database has been developed, it would enable the use of a thermotolerance hierarchy that could provide assurances to regulators that an existing treatment schedule would control a new pest species and avoid unnecessary duplication of costly research. Furthermore, acceptance of temperature profiles and other techniques by regulators would expedite the commercial implementation of non-MB quarantine treatments.

7.7.1.8 Irradiation

Irradiation typically refers to the process of treating commodities with ionising energy and includes gamma rays, accelerated electrons and X-rays . Gamma and x-rays are efficient ionising energies for quarantine purposes as they easily penetrate the commodity, but electron beam can also be used under the right circumstances. A summary of irradiation is provided by Burditt (1994) and by the Institute of Food Science and Technology (Anon 1999). Lacroix and Vachon (1999) reviewed the application of irradiation in combination with other treatments on strawberries, mangoes and mushrooms. Treatment by ionising radiation (gamma, x-rays and electron beam) has been approved for use in over 36 countries on more than 40 foodstuffs including vegetables and fresh fruit (Anon 1987a).

Irradiation can control many pest species and has additional advantages of allowing the commodity to be treated in the final packaging with no appreciable increase in temperature. Successful use of low dosage irradiation from isotope or electron beam sources depends on breaking the life cycle of the pest, usually resulting in sterility but sometimes mortality, without reducing the value of the commodity. Shelf-life extension should not be expected at low disinfestation doses (less than 1000 Gy) but often occurs. Considerable research on changes to commodity quality indicates irradiation is suitable for some fruits, vegetables and cut flowers (Anon 1986a, Kader 1986, Hayashi and Todoriki 1996).

Hallman (2000) reviewed the potential of ionizing radiation as a disinfestation treatment for insects other than tephritid fruits flies. Female insects, but not always mites, were reported to be sterilized with equal or lower doses than males. Low oxygen conditions often increase radiation tolerance. Insects in diapause were not more radiation-tolerant than non-diapausing ones. Some pests of several groups such as aphids, whiteflies, weevils, scarab beetles and fruit flies may be sterilised by exposure to less than 100 Gy while some lepidopterous pests and most mites required about 300 Gy. Stored product larvae required as much as 1,000 Gy to sterilise, and nematodes could need more than 4,000 Gy.

The internationally accepted CODEX dose limit for food irradiation is 10,000 Gy (IAEA 1991). The United States allows disinfestation of fresh foods up to 1000 Gy (Anon 1986a), which has encouraged use in commodity disinfestation. The International Atomic Energy Agency's (IAEA) International Group on Food Irradiation (ICGFI) has produced several reports on the use of irradiation as a disinfestation treatment for fresh fruits and vegetables (ICGFI 1991ab, ICGFI 1994). The FAO/IAEA also coordinated a research programme, initiated in January 1999, to promote the use of irradiation for quarantine treatments. In order to avoid unnecessary disinfestation experiments, FAO/IAEA recommended a minimum dose of 150 Gy, which is considered effective regardless of the fruit fly species (Loaharanu 1998). This programme also developed recommended minimum doses for mites (150-320 Gy), Diptera (100 Gy), other insects not specifically tested (> 300 Gy) and nematodes (> 4,000 Gy). IAEA reports that many types of fruit and vegetables and some cut flowers tolerate all these doses, except those applied for nematode control, and suggests irradiation would be suitable as a quarantine treatment in many circumstances. Some of these treatments could replace existing MB treatments.

USDA-APHIS published a final rule establishing phytosanitary requirements, allowing the use of irradiation treatments for imported fruits and vegetables (USDA 2002). The regulation rule establishes irradiation doses for 11 fruit flies and one seed weevil. The treatment is based on the pest requirements rather than on the commodity. The key elements of the rule address critical control points including irradiation doses and safeguarding after treatment. This means that any commodity can be irradiated at the proper minimum dose for any of these species. For commodities where more than one pest is present, the highest dose is required. If other pests of quarantine significance are also of concern on a particular commodity but are not listed in the rule, then irradiation is not considered to be an adequate quarantine treatment for that commodity. For example, if the quarantine pests of concern for a particular host are the melon fly that is listed in the rule and a noctuid moth that is not listed, then a different approved treatment must be used to mitigate the risk caused by the moth.

APHIS is establishing irradiation treatment to allow bell peppers, eggplant, mangoes, pineapple, Italian squash, tomatoes and gardenia flowers potentially infested with fruit flies and other pests to be moved from Hawaii to the mainland USA once treated with irradiation at a minimum dose of 250 Gy (Anon 2000b; Anon 2002c). Irradiation must be carried out in Hawaii or in non-fruit fly supporting areas in the USA, the commodity must be packed in pest-proof cartons after treatment, and there must be documentary proof of irradiation. The final rule concerns additional provisions for monitoring of foreign facilities that provide the treatments (Anon 2002g).

The Australia and New Zealand Food Authority has received an application in 2001 to amend "Standard 1.5.3-Food Irradiation" to permit the treatment with machine-sourced electron beam or x-rays of tropical fruit including breadfruit, carambola, custard apple, litchi, longan, mango, mangosteen, papaya and rambutan (Anon 2001e). The treatment aims to improve market access without using chemical treatments for pest control. Submissions on the proposal closed on 7 August 2002 and the application is under consideration.

Smittle (1997) has suggested that the 250 Gy level is higher than necessary now that dosimetry methods can be calibrated to national (in the USA) and international standards. Phillips *et al.* (1997) reported 150 Gy achieved a Probit 9 level of security for *Bactrocera latifrons* infested in green peppers in Hawaii. A minimum of 300 Gy was recommended for insects other than fruit fly and mites (ICGFI 1989). Proposing 'prevention of pupation' as a criterion of irradiation treatment efficacy rather than 'non-emergence of adults' was considered practical for determining the efficacy of irradiation for controlling tephritid fruit flies that have a diapause (over-wintering) stage (Hallman and Thomas 1999). This criterion would allow research results to be known in a less than a week rather than several months. Based on irradiation trials using this criterion, apple maggot *Rhagoletis pomonella* and blueberry maggot *R. mendax* were prevented from pupation when treated with 58 and 24 Gy respectively when irradiated as third instars in fruit.

Among the factors currently influencing further adoption of irradiation for disinfestation are consumer, industry and regulatory acceptance. Recently, however, acceptance of irradiated food has improved. The number of stores selling irradiated food and the quantity sold on the mainland USA continues to increase. Recent estimates indicated that over 3000 stores sold irradiated food in the US (Anon 2002i). Volumes of food irradiated in Europe are also significant; with more than 28 billion pounds reported annually (Anon 2000b). Other factors affecting adoption of irradiation are insufficient commercial-scale assessments of cost-benefit, and verification of treatment by inspection authorities. There is also the potential for irradiation-sterilised insects to be imported with live viruses as the sterilisation dose for insects is much less than the disinfestation dose for viruses.

To address some of these issues in the USA, USDA-APHIS several years ago permitted test shipments of Hawaiian produce to the Chicago region for irradiation to control pests potentially infesting a range of tropical commodities such as atemoya, banana litchi, melon, orange, papaya, rambutan and starfruit. A commercial X-ray facility opened in Hawaii in 2000 which allowed pre-shipment irradiation treatment of Hawaiian produce under USDA inspection.

USDA-APHIS has approved a regulation on the use of irradiation as a quarantine treatment (Anon 1996d). The USDA also held a plant quarantine workshop for regulatory personnel and intends to accelerate the work toward identifying the data and research needed for additional dose recommendations, particularly for generic doses (Griffin 1996). Starting irradiation research on US-based irradiation of papaya from Belize has commenced as a precaution in the event that fly-free certification is lost due to accidental importation of fruit flies. Papaya from Belize, Hawaii, Mexico and Chile potentially infested with fruit fly and exported to the US must 1) originate from an area certified free of fruit fly; 2) have undergone an approved heat treatment (vapour, single or multi-stage HTFA); or 3) have been irradiated (Hawaii only) (Miller and McDonald 1998).

Verification that a live insect intercepted on arrival has been treated with irradiation could be important to some regulatory authorities. Previous research has shown that irradiation increases the size of the supraoesophageal ganglion in insects (Rahman *et al.* 1990) as well as altering melanisation and phenoloxidase levels (Smittle and Nation 1995). Despite these results, these types of changes have not been approved as a verification method by plant regulatory authorities. Recently, the USDA prepared a final rule detailing packaging, inspection and record-keeping requirements to avoid uncertainty upon arrival of irradiated imported fruits and vegetables (Federal Register Oct 23, 2002)

In durable products, bamboo ware, toys, rugs, medicinal herbs and other items usually from countries in the Asia-Pacific region that are considered by the regulatory authority to be potentially infested or infested, are irradiated in Australia, thereby avoiding MB use (M. Marcotte, pers. comm. 2002).

Several areas have been suggested as considerations for future research that examine the impact of irradiation on commodities including pre- and post-harvest treatments, harvest maturity, time between harvest and treatment, post-treatment storage conditions, the physiological basis of tolerance and the potential for conditioning treatments and objective measurements for recording damage and relating these to biochemical indices (McDonald and Miller 1995). Examples of objective measurements for mango, carambola and grapefruit have been provided by McDonald and Miller (1994).

7.7.1.9 Modified atmospheres (MAs)

Perishable products in a container or film respire and modify the surrounding atmosphere to such an extent that it not only extends its shelf-life but can also become insecticidal. Unlike controlled atmospheres (CAs) that are generated externally and can be controlled to give atmospheres that have a specific oxygen (low) and carbon dioxide (high) composition, the composition of the atmosphere and the time to establish equilibrium in modified atmosphere situations is not easily predictable as it depends on the type of commodity and the biological process of fruit respiration which, for example, increases with increasing temperature.

Modified atmospheres (MAs) are typically generated by wrapping various types of *polyfilms* around the commodity (Shetty *et al.* 1989). In some cases, the commodity is palletised and wrapped and then flushed with gases to establish the desired atmosphere. Film permeability varies with film type and temperature, making MA control difficult under the changing temperatures commodities may experience in transit. Consumers, however, may eventually limit the widespread use of this technology due to possible concerns with excessive use of packaging materials.

Application of specialised *coatings* made of wax or cellulose to citrus has proven effective in the laboratory for killing Caribbean fruit fly (Sharp 1990). Wax treatment of a commodity may not be acceptable to the consumer.

MA appears particularly suitable for controlling pests on perishable products that can be stored for at least 7 days such as strawberries. However, there are currently no commercial examples of using MA for disinfestation of perishable commodities mainly because the atmospheres are, by definition, not controllable and repeatable. Regulatory agencies use controllability and repeatability as (implicit) criteria for acceptance of a quarantine treatment.

Specialised films for maintaining commodity quality using atmosphere-absorbing compounds impregnated into the film are becoming available. Such films are called 'active packaging' and are sometimes temperature activated. They are likely to be important in the future, particularly if they have a disinfestation role rather than just their current focus of increasing shelf-life mainly by ethylene absorption.

Recently, Finkelman *et al.* (2001) and Navarro *et al.* (2001) showed modified atmospheres for 3-7 days with 22 – 75 mm Hg abs. pressure contained within 15m^3 plastic cube containing 7 tonnes of cocao beans were effective in killing *Ephestia cautella* and *Tribolium castaneum*. This system would have application as a pre-shipment treatment for many countries that may require control of non-quarantine stored product pests intercepted on entry.

7.7.1.10 Physical removal

Water under high pressure has been shown experimentally to remove large numbers of pests from the fruit surface (Honiball *et al.* 1979, for scale insects, Yokoyama and Miller 1988, for codling moth eggs). Air under positive or negative pressure has also been used experimentally to remove pests, but not in sufficient numbers to be acceptable as a disinfestation treatment. These treatments are only suitable for removing pests on the surface of fruit such as accidental contaminants (‘hitch-hikers’) scale insects and mealybugs. The choice of air or water depends on the tolerance of the commodity to the treatment or convenience of use in the packing operation.

Removing bark from logs prior to export is practised widely as a control measure against timber pests, particularly bark beetles, which reduces the need for MB. The presence of bark on wood is essential for egg laying with some insects, notably certain longhorn beetles and wood wasps. Bark removal can destroy the habitat where bark beetles breed and their larvae feed. Once removed the wood is unsuitable for bark beetle breeding. Debarking, together with conversion to sawn timber in country of origin, appears to have potential to reduce the need for MB where bark-borne pests are the object of the treatment, including quarantine treatments. Wood that is green or freshly cut is easier to debark than dry or seasoned wood. Debarking had some advantage in pest control but could lead to lower pulp yield and quality, according to an EU funded research project (BioMatNet item AGRE-0057 1993).

7.7.1.11 Immersion

Under water dipping treatment of logs in seawater for plywood is a necessary process as it improves the quality of the products. Providing the treatment is longer than 30 days and an insecticide spray is applied to the surface it is an effective quarantine treatment. In Japan, approximately 14% of the logs imported in 1992 were treated using this technique, replacing the alternative methyl bromide treatment (Reichmuth 2002).

7.7.2 Chemical postharvest treatments

Chemical treatments consist of using fumigants or immersing commodities in dilute insecticides ('chemical dips').

7.7.2.1 Chemical dips

Commodities can be dipped in a dilute pesticide solution after harvest to kill targeted pests that might be present in or on the commodity or plant. The dip must be able to reach pests often well-hidden within the leaves and flower parts of plants but must not be phytotoxic. Appropriate precautions must be taken by packhouse personnel when carrying out the treatment and when the chemical is discarded.

Some countries discourage the use of chemical dips because of consumer concern for chemical residues, or because disposal of the pesticide solution after treatment is often environmentally unacceptable. For these reasons, a chemical dip is usually restricted to non-edible commodities such as ornamental plants, bulbs, nursery plants and cut flowers. Other countries such as New Zealand and Singapore accept chemical dips providing the maximum residue limits in edible commodities are not exceeded.

Australian tomatoes exported to New Zealand are dipped in dimethoate insecticide to control Queensland fruit fly (*Bactrocera tryoni*) (Heather *et al.* 1987) potentially infesting the commodity. Insecticidal dip is one of the most common post-harvest treatments for cut flowers (Hara 1994) and likely to become even more widespread as an alternative to MB in the future. Fluvalinate, a synthetic pyrethroid, is registered for use on cut flowers in the USA and its use has been recommended as a dip for tropical foliage plants imported into the USA (Osborne 1986).

7.7.2.2 Contact insecticides

Where registered for use, *contact insecticides* may provide persistent protection against reinfestation. In some situations, the use of dichlorvos offers a direct alternative to MB, for disinfestation of bulk grain during turning or loading at point of export. Contact insecticides are not normally registered for use on processed commodities or dried fruit, nuts and cocoa and dichlorvos has been deregistered in several countries where it was previously used for grain.

Contact insecticides, including dichlorvos, may be used as part of a pest management strategy. There is an approved quarantine treatment involving immersion of logs in water and treating the upper surface of the logs above the water level with an insecticide mixture (see Section 7.9.7). In the USA and Japan, a dip-diffusion treatment in a solution of borate is registered for sawn timber. Australia allows pressure impregnation of insecticidal mixtures as an alternative to methyl bromide for treatment of wooden pallets for control of *Sirex* and other wood pests.

Aerosol formulations using pyrethroid or dichlorvos insecticide have been used to meet phytosanitary requirements for cut-flower exports from some countries such as New Zealand (Carpenter and Stocker 1992), Australia and Malaysia.

7.7.2.3 Fumigation

This is the act of releasing and dispersing a pesticidal chemical so that it reaches a pest completely or partially while in the gaseous state. Yokoyama (1994) summarised fumigation treatments in use, treatments under development, methods of developing disinfestation treatments and fumigant residues. Fumigants generally penetrate well and are particularly suitable for killing pests that could be inside the commodity. However, they are not favoured by a segment of consumers that seek food with no pesticide residues. Registration of new chemical fumigants is also costly and time consuming as most countries now require extensive safety tests.

Fumigation treatments are usually carried out under very specific parameters to achieve complete pest mortality without damaging the commodity. For example, phosphine, sulphur dioxide and hydrogen cyanide require very low chemical concentrations, temperatures and exposure periods compared with MB to kill pests within the conditions known to be tolerated by the commodity. Fruit injury when used outside of the tolerance range for MB fumigation include browning, softening and scald (Meheriuk and Gaunce 1994). Methods for avoiding injury using carbon absorbers (Kawakami and Soma 1991) and diphenylamine (DPA) treatment (Sproul *et al.* 1976) have been well documented. Bond (1984) provides details of fumigant properties and methods of application. Many fumigants must be used cautiously due to their inherent physico-chemical properties and threats to human safety.

7.7.2.4 Carbon disulphide

Carbon disulphide (CS_2) has been used in the past for fumigating both durable and some perishable commodities. Because it is extremely hazardous due to its flammability and explosiveness, it is usually mixed with non-flammable products (Stark 1994). Historically, it has been used on fresh products (Osburn and Lipp 1935), nursery and growing plants as a quarantine treatment (J. Banks pers. comm. 2002).

7.7.2.5 Carbonyl sulphide

Carbonyl sulphide has been patented as fumigant. It has been categorised as a fumigant potentially suitable for controlling pests in soil as well as those infesting durable and perishable commodities (CSIRO 1993). Viljoen and Ren (2001) also found carbonyl sulphide had good penetration properties through both hard and soft timber. Carbonyl sulphide is being tested in the USA on lemons and nectarines.

7.7.2.6 Cyanogen

Cyanogen is a potent biocide that penetrates both hard and softwood timbers more quickly than MB and is reported to control insects, nematodes, fungi and bacteria (Viljoen and Ren 2001, Viljoen and Ren 2002). Wright *et al.* (2002) reported that the first international trials on cyanogen (C_2N_2) on timber for control of the Asian long-horned beetle had taken place in 2002 and further trials were expected in Malaysia (late 2002) and China (2003).

7.7.2.7 Ethyl formate, methyl formate and acetaldehyde

Although there has been an interest in the past in the use of plant volatiles such as separate applications of ethyl or methyl formate and acetaldehyde (Aharoni *et al.* 1979, Stewart and Mon 1984, Wright *et al.* 2001), none are currently registered as fumigation treatments. Ethyl and methyl formate are inflammable and explosive when mixed with air at concentrations required to kill pests, but formulations in CO_2 are under development to reduce this risk. Ethyl formate is less pesticidal than methyl formate on a weight for weight basis. Acetaldehyde is more effective as a fungicide than an insecticide but its safety for humans has been questioned (Woutersen *et al.* 1984).

7.7.2.8 Hydrogen cyanide

Hydrogen cyanide is used as a disinfestation treatment on fresh commodities for control of pests such as thrips, white flies, scale and aphids (Bond 1984), particularly on products imported by Japan. It is still in use in India for imports of cotton and cotton goods and is used in several countries for pest control in transport, including aircraft. However, not all countries allow hydrogen cyanide to be applied as a pesticide as there are concerns for human safety with this highly toxic material. Many countries have withdrawn registration because of health concerns and lack of commercial support (J. Banks, pers. comm. 2002).

7.7.2.9 Methyl iodide

Methyl iodide is being tested in the US mainly as a soil fumigant, but there is also interest in using it for postharvest disinfestation on lemons and nectarines. Waggoner *et al.* (2000) described methyl iodide as being at least as effective for control of quarantine insect pests as MB.

7.7.2.10 Methyl isothiocyanate

Methyl isothiocyanate (MITC) controlled forest pests in timber, notably pine wood nematode (Naito *et al.* 1999).

7.7.2.11 Phosphine

Fumigation of logs in the USA using phosphine was effective for controlling bark beetles, wood-wasps, longhorn beetles and platypodids. For durable commodities, phosphine is becoming less attractive as this fumigant faces pest resistance and corrosiveness that may collectively reduce its ability to replace remaining MB uses (see Chapter 6 on durable commodities for further information). Recently, pure formulations of phosphine have proven effective in Japan for controlling two-spotted spider mites without injuring apples and grapes.

7.7.2.12 Sulphur dioxide

Sulphur dioxide is used mainly for fungus control in cool stored grapes and recent research has shown a potential to control mealybug and moth pests.

7.7.2.13 Sulphuryl fluoride

Sulphuryl fluoride is mainly used for controlling wood-destroying pests in residences and other buildings. It controls a wide range of pests including bark beetles, wood wasps, longhorn beetles and powderpost beetles. It is under consideration for registration for food uses in come countries (Drinkall 2002, Voglewede *et al.* 2002).

Sulphuryl fluoride is approved by USDA-APHIS and the Australian Quarantine Inspection Service as a quarantine treatment for beetles and termites in wood products. In addition, USDA-APHIS has authorised a quarantine treatment for ticks. The low reactive potential of sulphuryl fluoride often makes it the fumigant of choice for non-food objects, in shipping containers, that may be damaged by other fumigants. However, recent tests of SF against Asian longhorn beetle developmental stages have shown survival of some stages at low temperatures even at high dosages. Even at 10°C, cold acclimated larvae require a *ct*-product in excess of 3000 g h m^{-3} for a quarantine level of kill with a 24-hour exposure (Barak 2002).

7.7.2.14 Combination treatments

Treatments may be combined to achieve required efficacy levels. The combination of two or more treatments, when the elements of each treatment are less 'harsh' than when used individually, often offers the advantage of controlling pests without damage to the commodity. As many single treatments cause damage, not unexpectedly, there is great interest in combination treatments – either carried out simultaneously, or one after the other. For example, MB fumigation combined with a short period of cold storage kills codling moth eggs on apples more effectively than either treatment alone (Waddell 1993). The *combination treatment* of 18 days *cold treatment* at 0°C (± 0.5°C) followed by MB *fumigation* at 12 g m^{-3} for 2 hours at 15°C for control of fifth instar diapause larvae of peach fruit moth potentially infesting apples for export to the USA was more effective than MB fumigation alone (Kawakami *et al.* 1994). A combination of *vapour heat* followed by *cold storage* is used to kill oriental fruit flies on litchi imported by Japan from Taiwan (Anon 1980) and China (Anon 1994a).

Inspection combined with a heat treatment is an accepted treatment for litchi exported from Hawaii to the mainland USA. Litchis must be thoroughly examined in the packhouse and found free of *Cryptophlebia* spp. and other plant pests. Fruit must be submerged at least four inches below the surface of the water which must be kept at 45.5°C and above for 20 minutes (Anon 2002f). Hydro-cooling is recommended after treatment to avoid fruit damage.

A mixture of MB, phosphine and carbon dioxide was registered for use in Japan for controlling arthropods intercepted on cut flowers (Anon 1995a). The MB dosage was two-thirds less with the gas mixture than when used alone (Kawakami *et al.* 1996). No injury was observed on chrysanthemums and orchids that are sensitive to MB fumigation.

In Germany and Japan a mixture of phosphine with sulphuryl fluoride has been investigated against forest insect pests but results were not significantly different from those with phosphine alone (Kawakami 1999).

The combination treatments cited above are the only commercially available treatments known to MBTOC to be accepted by regulatory agencies. The rarity of combination treatments compared with single treatment applications is probably due to extensive technical documentation required to demonstrate treatment efficacy for regulatory agencies.

7.7.3 Other methods

Novel research is investigating the use of micro-second pulses of high voltage *electricity* for controlling pests in citrus as a potential replacement for MB (Hardin 1999). The treatment was reported to not affect fruit quality since very little heat was generated.

Industrial radiofrequency (RF) and microwave systems are claimed to heat the pest faster (10-20 ºC per minute) than heat treatments using hot air or hot water and may therefore be more suitable as a quarantine treatment. Advantages of RF are that it is efficacious, treatments are short, and damage to heat-sensitive commodities can be avoided. However, it has the disadvantages of high capital cost and is energy intensive.

Accurate and rapid identification of intercepted species as non-quarantine - often of only one insect specimen - can avoid fumigation with MB, or avoid destruction costs if no alternative is available. Armstrong *et al.* (1997) reported on the ongoing development of a molecular technique for distinguishing most species of fruit flies within the genus *Bactrocera* that potentially infest tropical commodity imports. Similarly, Beuning *et al.* (1999) report on a molecular technique for distinguishing a quarantine species of mealybug from closely related non-quarantine species potentially intercepted on apple exports to the USA.

7.8 Existing and Potential Alternatives for Perishable Commodities

The principal perishable commodities that use MB as QPS treatments are apples and pears, berryfruit, citrus, cucurbits, cut flowers and ornamentals, grapes, root crops, stonefruit, subtropical and tropical fruit, and some vegetables. The principal durable commodities that use MB as QPS treatments are bulbs; dried fruit, nuts, coffee and cocoa; grain; museum artefacts; timber and wood products; tobacco and cotton; seeds for planting; and wood packaging materials. Occasionally, empty ships, freight containers and other vehicles are fumigated with MB prior to loading. Farming, military and other equipment that has been contaminated with pests of quarantine significance can also be decontaminated using MB.

Discussed in this section are examples of disinfestation treatments previously reported (MBTOC 1995, 1998), those that have been investigated and commercialised since 1998 and those with potential for implementation within the next 2-5 years. While most examples are ‘new’ treatments rather than replacements for ‘existing’ MB treatments, they serve to illustrate the investment in a range of commercial options that will avoid further dependency on MB. Within each commodity group, alternative treatments discussed in this Section have been *italicised* in order to highlight their use with particular commodities.

7.8.1 Apples and pears

Although apples and pears are infested by a large number of pests, for most countries codling moth, fruit fly, mites, scale insects and fire blight bacterial disease are the major pests and diseases of quarantine concern.

MB has been rarely used for controlling pests on apples and pears. However, due to approval by Japan of disinfestation treatments for codling moth developed in the last 10 years, relatively small quantities of MB are now used on apple exports to Japan from Australia (Tasmania), France, New Zealand and the United States. A similar MB-based treatment may also be used on exports of apples from the USA to Korea if the treatment is approved by the Korean regulatory authority (Hansen *et al.* 1999).

7.8.1.1 Existing alternatives

There are few commercial treatments for apples and pears to control pests. *Pre-shipment certification* is carried out successfully by several countries exporting to the United States, including New Zealand and Chile. *Controlled Atmospheres (CAs)* combined with cold storage have been used to kill scale insects on apples exported from Canada to California (Dickler *et al.* 1975). USDA-APHIS approves a *cold* treatment to control fruit fly in apples or pears imported into the United States from Chile, France, Israel, Italy, Jordan, Mexico, South Africa, Spain and Uruguay (Anon 2002f). *Irradiation* is used to increase the shelf-life of apples on a small scale in China (Xu *et al.* 1993). A *systems approach* has been accepted by Taiwan for New Zealand and Australian apples (T. Batchelor, pers. comm. 1998); and for Brazilian apples to the United States (John Thaw, USDA-APHIS, pers. comm. 1998).

7.8.2 Potential alternatives

CA at low temperature kills some lepidopterous species, but short duration and therefore less costly treatments may be achievable by combining CAs with heat, or by using heat alone.

'Packham Triumph' pears exposed to *heated CA* atmosphere of <1 kPa O_2 for 30 hours at 30°C followed by one month of cold storage in air gained 100% mortality of major Australian apple and pear pests *Epiphyas postvittana*, *Cydia pomonella* and *Grapholitha molesta* (Chervin *et al.* 1997). Implementation of such treatments was not considered to be costly for fruit industries already equipped with CA facilities. There is a need to gain a better understanding of pest and fruit physiology under CA/heat or heat alone in order to optimise treatment parameters.

A codling moth *pest-free zone* is feasible in Western Australia since this pest is absent in apple and pear production areas. Sterile codling moths were released in the Okanagan Valley region in Canada to establish a pest-free zone (Proverbs *et al.* 1982).

A *systems approach* may be feasible for some commodities in the USA and Canada where, for example, a reduction in codling moth populations in apples has been documented for some packhouse operations in Washington State (Hansen *et al.* 1997). This study showed that only 71 codling moths were found in over 160,000,000 fruit surveyed in three years. Thus, the combination of pest control in the field and culling in the packhouse has reduced the risk of contamination for apple exports to levels that meet and often exceed current levels of quarantine security in international trade.

New Zealand MAFF is reported to be allocating resources to investigate appropriate methods for quantifying the efficacy of field control programmes for a number of exports including apples as these are considered at least equivalent by New Zealand to fumigation with MB (Ivess 1995).

New Zealand Royal Gala apples tolerated 44°C for 35 minutes followed by 7 or 10 weeks of cold storage at 0.5°C (Smith and Lay-Yee 2000). Early-harvest fruits had lower levels of damage than mid- and late-harvest fruits. This treatment is effective in controlling the quarantine leafroller pests *Epiphyas postvittana*, *Planotortrix octo* and *Ctenopseustis obliquana.*

Heat (35 and 40°C) and CA (0.4 – 21% O_2) was also effective in controlling *Pseudococcus affinis* scale in less than 15 hours making this a possible disinfestation treatment for New Zealand apples exported to markets that have concerns for this and other species of scale insects (Whiting and Hoy 1997, Whiting *et al.* 1999b). Some varieties of New Zealand apples were reported to be tolerant of many of the combinations of CA and heat and therefore one or more combinations have potential as quarantine treatments (Lay-Yee *et al.* 1997a).

Leafroller and mite pests are major impediments to exports of fresh fruit from New Zealand, particularly apples and kiwifruit. Whiting *et al.* (1995, 1996) reported on a range of air or CAs (2% O_2; 5% CO_2) combined with heat (up to 40°C, see Hoy and Whiting 1998) that have potential to control leafroller pests on export apples and kiwifruit. Kiwifruit where not damaged when exposed to temperatures up to 40°C in air for as long as 10 hours followed by cooling in ambient water or air and stored for 8 weeks (Lay-Yee and Whiting 1996). Kiwifruit tolerated shorter treatments at elevated temperature under the CA.

Whiting *et al.* (2002eb) reported that *physical removal* using high-pressure water treatments, and some with a warm water pretreatment, were effective at removing mealybug (*Pseudococcus viburni*) and *E. postvittana* quarantine pests, and a range of insect contaminants, from New Zealand apples and kiwifruit. The process and machinery for the apple treatment has been patented. There was no increase in fruit damage compared with standard packhouse procedures (Whiting and Jamieson 1999). These results indicate commercial implementation of high-pressure water jet technology could be successful in reducing the incidence of quarantine pests detected before shipment of export fruit and avoiding the potential for MB fumigation on arrival.

The response of all stages of codling moth to *irradiation* has been defined (Burditt and Moffitt 1985). Similarly, *Ctenopseustis obliquana* leafroller eggs and larvae were prevented from completing further generations when exposed to only 70.1 Gy, a dose that is unlikely to damage apples (Lester and Barrington 1997). 'Red Delicious' apples irradiated at up to 1000 Gy were marketable even after 11 months storage (Olsen *et al.* 1989). Drake *et al.* (1999) investigated the effect of 300 to 900 Gy irradiation on control of apple and pear diseases and the impact of doses in this range on fruit quality. Apples irradiated at 600 Gy followed by regular or *CA* (1.5% O_2; 1.5% CO_2) cool storage were not damaged, but San José scale (*Quadraspidiotus perniciosus*) mortality was inconsistent from year to year (Angerilli and Fitzgibbon 1990). More recently, the 5 instars of codling moth were irradiated at doses of 0, 100, 300, 600 and 900 Gy and phenoloxidase levels were monitored at 0, 2, 4 and 6 days after treatment (Neven and Morford 1998). No significant change in the protein levels, enzymatic activity, or melanisation rates in irradiated codling moth larvae was found.

Hallman and Thomas (1997) confirmed that apples could readily tolerate 300 Gy if a disinfestation-effective dose of <100 Gy was applied to control apple maggot, blueberry maggot and plum curculio. A dose of 90 kGy or less was considered acceptable as a quarantine treatment for apples as changes in quality grade, firmness, acid content and external-internal colour were not sufficiently evident to reduce marketability (Drake *et al.* 1998).

Hallman and Martinez (2001) have proposed a low-dose gamma irradiation quarantine treatment to control the Mexican fruit fly (*Anastrepha ludens*) in citrus, based on prevention of adult emergence. Depending on the level of quarantine security required, the minimum absorbed dose would be 58 or 69 Gy. When applied on the commercial scale, many irradiated fruits in each load could be expected to receive three times the minimum required dose for treatment efficacy. Several quality parameters of grapefruit, oranges and tangerine were not affected when treated up to 500 Gy.

A *combination fumigation* treatment consisting of MB (10 g m^{-3}) and phosphine (3 g m^{-3}) at 15°C for 4 hours killed the most tolerant stage (the egg) of Kanazawa spider mite, a pest potentially present on apple exports from Japan to the USA (Mizobuchi *et al.* 1997).

Codling moth exposed to carbonyl sulphide at 80 g m^{-3} resulted in 87% mortality compared to 100% mortality at 25 g m^{-3} methyl iodide (Leech *et al.* 2001). The phytotoxic response by apples to carbonyl sulphide was not reported.

Phosphine generated from magnesium phosphide or aluminium phosphide pellets generates ammonia and phosphine by-products that are toxic to perishable commodities. Recent research with pure phosphine reduced and in some cases eliminated commodity phytotoxicity. ‘Ohrin’, ‘Kinsei’ and ‘Fuji’ apples were undamaged by *phosphine fumigation* (3 g m^{-3} for 18 - 24 hours at 15°C) suggesting that this could be a disinfestation treatment for mites in the future (Soma *et al.* 1997b). No injury was observed on Nijisseiki pears fumigated with phosphine at 1-3 g m^{-3} for 24 hours at 15^{O}C (Soma *et al.* 1997ab; 1999). These concentrations killed *T. urticae* but not the peach fruit moth (*Carposina niponensis*). In Japan, mites *Tetranychus urticae*, *T. kanzawai* and *Eotetranychus sexmaculatus* were controlled by 2 g m^{-3} phosphine at 15^{O}C for 16-24h on Japanese apples and pears without damage to the fruit (Kawakami 1999).

Phillips *et al.* (2002) showed that 0.3 g m^{-3} *phosphine* (from ECO_2FUME formulation consisting of 2% phosphine and 98% carbon dioxide) achieved 100% mortality in 48-72h of all stages of apple maggot *Rhagoletis pomonella* fruit fly infesting apples. This dose did not affect the quality of Red Delicious apples and showed potential as a quarantine treatment to replace MB for apple exports.

New Zealand apples were exposed to an insecticidal *heat* treatment of 40°C for 17 or 20 hours in an atmosphere of 1.2% O_2, 1% CO_2 followed by cool storage in air. No significant damage was observed in ‘Royal Gala’ apples but ‘Granny Smith’ showed some damage (Lay-Yee *et al.* 1996). Both varieties were firmer when heat-treated under

CA rather than air suggesting their shelf life may have been improved. 'Granny Smith' apples, immersed in 45°C water for up to 40 minutes, were not damaged by the treatment (Spooner and Lay-Yee 1995). These apples also tolerated exposure to higher temperatures or for longer periods provided they were first exposed to air at 38°C.

A two-component quarantine treatment (55 days coolstorage at 2.2 ºC or below followed by 56 g m^{-3} MB for 2h at 10 ºC) proved effective in controlling codling moth (*Cydia pomonella*) in Golden Delicious, Braeburn, Fuji, Gala, Jonagold and Granny Smith apple cultivars intended for export to Japan and Korea (Hansen *et al.* 2000).

Increased pesticide resistance of mealybug on New Zealand apples has resulted in increased incidence of this quarantine pest on harvested apples which, in turn, has raised the concern of regulatory authorities in the United States and some South Pacific countries. Large-scale trials using mealybug artificially infested on apples showed this pest could be effectively controlled by 42 days coolstorage at 0^{o}C (Hoy and Whiting 1997) rather than using MB fumigation.

Neven and Drake (1997a) listed 12 *heat* treatments for codling moth control in apples and pears that varied in: (1) the rate at which the target temperature was achieved (4 - 12°C per hour); (2) the target temperature (44 - 46°C) and the duration of the treatment at the target temperature (2 - 18 hours). All 12 treatments provided control of codling moth and resulted in acceptable quality of 'Red Delicious', 'Golden Delicious', 'Fuji', 'Granny Smith' apples; and 'd'Anjou' and 'Bosc' pears. Further research is required to test the most promising treatments using sufficiently large numbers of insects acceptable to quarantine authorities.

Heat treatments using a computerized water bath system and linear heating rate were studied on the mortality of 5th instar codling moth (Neven 1998). The study showed that the slower the rate of heating, the longer the exposure to the final treatment temperature was needed to achieve 95% mortality.

Lewthwaite *et al.* (1999) tested the responses of lightbrown apple moth larvae (*Epiphyas postvittana,* LBAM*)* on apples to immersion in solutions of sodium bicarbonate at 20-45 ºC. The results showed that 60 minutes immersion in 5% sodium bicarbonate solution at 20 ºC resulted in a maximum of 60% mortality. Up to 100% mortality was achieved by increasing the immersion temperature to 45 ºC. However, enhanced mortality was attributed to the temperature rather than sodium bicarbonate. All of the emulsifiers added to 3% sodium bicarbonate increased mortality.

Mortality responses were determined for fifth instar LBAM, in ethanol solutions and exposure to ethanol vapor at arrange of concentration and temperatures (Dentener *et al.* 2000). Mortality for larvae immersed on apples in a range of ethanol concentrations was higher than for larvae in the absence of apples. Increasing treatment temperature from 20 to 45 ºC during ethanol immersion significantly increased larval mortality. During ethanol vapor exposure, longer treatment times were required to achieve 99% mortality of larvae on apples compared with those in the absence of apples.

Pears were considered likely to tolerate a disinfestation *CA* treatment for the two-spotted spider mite (*Tetranychus urticae*) consisting of 5.5 days under 95% CO_2 in air at 0°C and a *combination treatment* consisting of a 1 day 'shock' treatment in 95%

CO_2 or 0.125% O_2 at 20°C followed by 18 days in air at 0°C (Zhou and Mitcham 1997).

A 25mm *vacuum* treatment for 48h at 25°C gave almost 100% mortality of apple maggot *Rhagoletis pomonella* fruit fly infesting apples and shows potential as a quarantine treatment to replace MB for apple exports (Phillips et al. 2002).

LBAM larvae were very susceptible to less than 5 ppm tebufenozide *chemical dip* for up to 7 days when incorporated into synthetic diet, and some stages even more susceptible to this chemical when combined with a high-temperature controlled atmosphere treatment (2% O_2, 5% CO_2, 40°C) (Whiting *et al.* 1999a). Very dilute concentrations of tebufenozide look promising for controlling this quarantine pest on apple exports to Japan, the United States and other countries.

Mortality of non-diapausing and diapausing two-spotted spider mite (*Tetranychus urticae*) on apples when immersed in dilute ethanol *chemical dips* at various temperatures is given in Dentener *et al.* (1998). Mites are pests on apples exported from New Zealand to Japan and are subject to quarantine restrictions.

LBAM larvae were exposed to a range of lufenuron concentrations (0-200 ppm) incorporated into synthetic diet (Whiting *et al.* 2000). Third and fifth instars displayed an increase in mortality earlier than first instars, and were more sensitive to the lower lufenuron concentrations in this range. Consumption of lower lufenuron concentrations by these larvae delayed pupation and resulted in pupal deformity. Third instars were exposed to sublethal lufenuron concentrations for 4 days and the fourth-instar survivors subjected to a controlled atmosphere cold storage treatment (2% O_2, 2% CO_2, 0.6 ºC). Larvae ingesting diet containing 0.5 ppm lufenuron required longer exposure to the postharvest treatment to achieve 95% mortality than larvae not ingesting the insect growth regulator.

7.8.3 Berryfruit

Berryfruit includes strawberry, raspberry, blueberry and blackberry. The main pests of quarantine concern are blueberry maggot and other fruit flies, thrips, aphids and mites.

Many countries require a mandatory MB fumigation for berryfruit imported from countries with fruit flies. If fruit flies are not of quarantine concern, berryfruit are imported upon inspection. Imports of blueberries into regions in Canada that do not grow blueberries are permitted.

7.8.3.1 Existing alternatives

Japan accepts strawberries from the Netherlands as free of Mediterranean fruit fly (host freedom) as the Netherlands is a pest-free zone for this pest (Anon 1993a). There are no other alternatives currently available for control of internal pests.

7.8.3.2 Potential alternatives

Irradiation shows potential for controlling blueberry maggot (*Rhagoletis mendax*) in blueberries (Miller *et al.* 1994).

Strawberries under *modified atmosphere* of about 10% CO_2 are commercially irradiated in Florida (Marcotte 1992) which may also allow phytosanitary control if required. Currently, strawberries are gassed with 15 - 20% carbon dioxide atmospheres (a modified atmosphere) for *Botrytis* control in-transit from California to other parts of the United States, a treatment that might also kill thrips and aphids.

Fumigation with separate applications of sulphur dioxide, carbon monoxide or hydrogen cyanide may be tolerated by some berryfruit crops, but the cost of commercial implementation of three consecutive treatments may be prohibitive.

Heat treatments may be suitable for controlling heat sensitive pests such as thrips (Lay-Yee *et al.* 1993) and cold treatments for control of tropical insects providing the exposure period is not detrimental to the shelf life of the berryfruit.

Coolstorage is the most widely used disinfestation treatment, applied mainly to control tropical and subtropical insect pests potentially infesting a range of berryfruit. Recent work shows potential for reducing coolstorage time for blueberries. Twelve days at 1.0 ºC was found to be sufficient to control *Bactrocera tryoni* (Queensland fruit fly) potentially infesting blueberries (Jessup *et al.* 1998). To minimise coolstorage costs and delays in marketing this perishable fruit to the USA and other markets from Australia, the researchers suggested the United States Department of Agriculture consider adding this shorter treatment to their current Animal and Plant Health Inspection Service – Plant Protection and Quarantine (APHIS-PPQ) treatment schedule that requires 18 days at 1.1 ºC or below.

A dose of 92 Gy was considered suitable as a quarantine treatment for plum curculio *Conotrachelus nenuphar* potentially shipped in blueberries (Hallman 1998). Doses of irradiation at about this low level are not likely to damage blueberries when irradiated commercially.

7.8.4 Citrus

Citrus includes oranges, grapefruit, lemons, limes, tangeloes, tangerines and pomelos. Although citrus are infested by a large number of pests, for most countries fruit flies, scale insects and Fuller's rose weevil are the main pests of quarantine importance.

MB often damages citrus at concentrations required to kill fruit fly, limiting its use.

7.8.4.1 Existing alternatives

Limes found to be infested with mealybugs (Pseudococcidae) and other surface pests can be treated with hot water as an additional option for imported limes found to be infested mealybugs and other surface pests at the port of arrival in the USA (Anon 2001a).

Some of the USDA-accepted treatments cause unacceptable damage to the fruit, are not economical or allow survival because of variation in fruit size. To avoid fruit damage, Mangan *et al.* (1998) demonstrated the acceptability of 210 minutes at 45°C for tangerines, 250 minutes at 46°C for oranges and 300 minutes at 46°C for grapefruit. Shellie and Skaria (1998) showed that such treatments may also inhibit green mold *Penicillium digitatum* growth. The treatment was shown to be an effective commercial replacement for MB and was accepted as a quarantine treatment in 1999 by USDA-APHIS. Commercial Hot Forced-Air Treatment (HTFA) operations have been constructed in Mexico for the treatment of citrus imported into the United States. Currently, USDA-approved treatments for grapefruit, orange and tangerine against Mexican fruit fly, *Anastrepha ludens,* include MB fumigation or vapour heat; and for grapefruit, cold treatment or multi-stage HTFA.

Japan accepts citrus from Florida exposed for 17 - 24 days to *cold* treatment at 2.2°C to control Caribbean fruit fly (*Anastrepha suspensa*) (Anon 1990a); citrus from South Africa after 12 days *cold treatment* at -0.6°C to control Mediterranean fruit fly (*C. capitata*); citrus from South Africa and Swaziland after 12 days cold treatment at -0.6°C to control Mediterranean fruit fly (Anon 1973); citrus from Israel after 13 - 16 days *cold treatment* at 0.5–1.5°C (Anon 1990b); citrus from Spain after 16 days cold treatment at 2.0°C to control Mediterranean fruit fly (Anon 1988b); citrus from Australia after 14 - 16 days cold treatment at 1°C to control Mediterranean fruit fly and Queensland fruit fly (*B. tryoni*) (Anon 1992); citrus from Taiwan after 14 days at 1°C to control oriental fruit fly (*B. dorsalis*) (Anon 1980); grapes from Chile after 12 days at 0°C to control Mediterranean fruit fly (Anon 1990c); and kiwifruit from Chile after 14 days at 0°C (Anon 1991) to control Mediterranean fruit fly.

USDA-APHIS accepts *cold treatment* for 11 - 22 days depending on the temperature for control of fruit fly species in some varieties of citrus from 23 countries (Anon 2002f). Included in these treatments is storage at 0.6 - 1.7°C for 18 - 22 days as a quarantine treatment against Mexican fruit fly for citrus imported into the USA from Mexico or Central America. However, this treatment is not used commercially because of problems with chilling injury (Shellie *et al.* 1997).

Sometimes conditioning at warm temperatures is necessary for citrus fruit to tolerate cold treatment (Houck *et al.* 1990a,b, Houck and Jenner 1995, Kitagawa *et al.* 1988). For example, in work with Arizona-grown desert lemons, curing fruit at 15°C and 95% relative humidity for one week significantly reduced phytotoxicity of fruit stored at 1°C for 2 - 6 weeks. Pre-conditioning lemons in air at 15°C for several days or in water at 55°C for 5 minutes induced biochemical changes which may improve citrus tolerance to cold temperature storage (Aung *et al.* 1997).

Hydrogen cyanide is used to kill scale insects on citrus. Individual applications of *carbonyl sulphide* and *methyl iodide* were not phytotoxic to fresh lemons and therefore both fumigants appeared promising (Obenland *et al.* 1998).

Heated dry air that increases the fruit centre of grapefruit to 47.8°C over at least a 3 hour period is an approved quarantine treatment to control Mexican fruit fly (*Anastrepha ludens*) (Anon 2002f). *Heated* moist air to a fruit centre temperature of 43.3°C and held for 6 hours is approved for control of this pest in grapefruit, orange and tangerine from Mexico (Anon 2002f) and pineapple imported from areas infested with Mediterranean fruit fly, oriental fruit fly and melon fly (Anon 2002f).

7.8.4.2 Potential alternatives

Novel research reported on the use of *electricity* for controlling pests in citrus as a potential replacement for MB. Microsecond pulses of up to 9,000 Volts, each lasting less than 1/20,000th of a second, were effective in killing fruit fly infesting citrus (Hardin 1999). Less than 3% of the eggs hatched, and of those that did, none formed adults. The treatment may not affect fruit quality since very little heat was generated.

An industrial partner is currently being sought to further explore the potential of using electricity as a quarantine treatment.

Researchers in the US are investigating the potential for a *systems approach* to be applied to Mediterranean fruit fly potentially infesting lemons (Aung 2001), based on peel resistance. This information will allow the use of lemon peel characteristics based on different maturities to predict fruit fly infestation and thus the appropriate level of mitigation that is required using a quarantine treatment.

Some citrus is individually wrapped with fungicidal film and the *modified atmosphere* generated may also kill pests if the film remains intact. Some MA treatments damage citrus (Houck and Snider 1969, Shahbake 1999) limiting its widespread use.

Shellie and Mangan (1997) reported that grapefruit *heated* at 10°C in 1% oxygen required 30% less exposure time than fruit heated in air to obtain 100% mortality of the Mexican fruit fly (*A. ludens)*. Further research on the same species showed that heating 'Rio Red' grapefruit at 44°C under 1% O_2 atmosphere for 2 hours shortened the treatment time by 30% to achieve 100% larval mortality than when the treatment was carried out in air enriched with 20% CO_2 (Shellie *et al.* 1997). Inconsistent fruit quality results warranted further tests.

The 99% lethal time dosage for the third instar Mexican fruit fly exposed to 44 ºC core temperatures in artificial fruit is 61.5 min when a slow heating rate (120 min ramp) is applied, but only 41.9 min when a fast heating rate (15 min ramp) is applied (Thomas and Shellie 2000). Thermotolerance can be induced under conditions used to commercially disinfest fresh citrus and mangoes and this highlights the necessity for specifying heating rates in quarantine treatment schedules.

Limes potentially infested with pink mealybug *Pseudococcus odermatti* imported from the Caribbean to the USA were disinfested by 20 minutes *heat treatment* in water at 49^{o}C (Gould and McGuire 1998; 2000). Soap, vegetable and petroleum oil coatings appeared to cause the mealybug to leave the fruit. More extensive entomological work with heat and waxes is required to develop a treatment undamaging to limes. Hot water immersion and *insecticidal coatings* were further tested to determine if they could be used to control *Planococcus citri* and *Pseudococcus odermatti* mealybugs. No insects or mites were found to survive after 20 minutes *heat treatment* in water at 49^{o}C (Gould and McGuire 2000). Four coatings were tested at a 3% rate: two petroleum-based oils (Ampol and Sunspray oil), a vegetable oil (natural oil) and a soap (Mpede). Ampol oil gave up to 94% mortality of mealybugs but this was not sufficient on its own to provide quarantine security. The coatings might be effective as a postharvest dip before shipment.

Texas researchers showed in experimental and commercial trials that coolstorage at 14^{o}C combined with ultra-low oxygen for up to 21 days could provide quarantine security against third instar larvae of the Mexican fruit fly (*Anastrepha ludens*) infesting 'Rio Star' grapefruit (Shellie and Mangan 1998, Shellie 1999). Well-controlled, ultra-low oxygen conditions may provide an alternative to MB for controlling Mexican fruit fly in citrus providing the incidence of some physiological disorders can be minimised.

McDonald *et al.* (1998) reported grapefruit damage was reduced when they were exposed for 2 hours to 20, 38 or 42^{o}C prior to *irradiation* at 1 kGy. Similarly, conditioning of lemons for 3 days at 15^{o}C before *methyl iodide* fumigation lessened lemon peel injury (Obenland *et al.* 1998).

Results from these experiments suggest that treatment in heated atmospheres low in oxygen has potential for disinfesting grapefruit of Mexican fruit fly, particularly if further work is based on thermal kinetics of fruit fly mortality and an understanding of plant physiological responses to stress at the cellular level. For example, based on a large set of mortality data generated from heat treatments for this fruit fly species, a kinetic model was shown to be the best predictor of the thermal death point likely to meet quarantine security levels (Thomas and Mangan 1997). In addition, developing storage practices that allow produce to adapt to disinfestation treatments and anaerobiosis conditions may be the key to implementing these treatments in commercial practice (refer to Chervin *et al.* 1996 for studies on cellular responses to low oxygen conditions). Brown *et al.* (1995) suggested using thermodynamic principles for predicting the final temperature of navel oranges dipped, flooded or sprayed with heated water to control mites, mealybug and lightbrown apple moth species.

Carbonyl sulphide, methyl iodide and sulphuryl fluoride *fumigants* were tested on lemons against California red scale (*Aonidiella aurantii*) (Leech *et al.* 2001). Lemons treated with the highest selected dosage of 80 g m^{-3} carbonyl sulphide gave only 87% kill of red scale, well below the desired probit 9 level. Methyl iodide gave 100% red scale mortality at more than 40 g m^{-3}, but caused significant fruit injury. Conditioning lemons at 15°C for 3 days before fumigation lessened lemon phytotoxicity. Forced aeration at 3.5 standard litres per minute of lemons for 24 h following fumigation at 20 g m^{-3} significantly reduced phytotoxicity compared to 2 h postfumigation aeration. Waggoner *et al.* (2000) considered *methyl iodide* a potential replacement for MB as preliminary tests showed no damage to lemons at concentrations effective against red scale (*A. aurantii*). Sulphuryl fluoride at more than 40 g m^{-3} gave 100% red scale mortality, but resulted in commodity phytotoxicity.

Phosphine fumigation was predicted to kill all stages of Mexican fruit fly larvae and pupae in 'Ruby Red' grapefruit after 4 - 7 days exposure at 0.125 g m^{-3} at 8 - 48°C and > 50% RH (Wolfenbarger 1995b). This variety tolerated 4 days fumigation with phosphine at 0.5 g m^{-3} under the similar environmental conditions indicating potential for a commercial disinfestation treatment.

In Australia, the cylinder-based phosphine formulation ECO_2FUME® has been shown to disinfest oranges from larvae of *Bactrocera tryoni*, pears from *Epiphyas postvittana* and apples from larvae of *Cydia pomonella* without injuring the produce (Williams and Ryan 2001).

California red scale *Aonidiella aurantii* infesting grapefruit were killed by separate *fumigations* of 1.5 or 3% acetaldehyde, ethyl formate and methyl formate (Aharoni *et al.* 1987). No phytotoxicity or off-flavours were detected in the fruit. These three plant volatiles have potential to control this insect pest on citrus.

Immersion of oranges intended for export to Japan from Australia in water at 50°C for 2 and 10 minutes and 52°C for 2 and 7 minutes, reduced egg hatch in the weevil

Asynonychus cervinus by up to 66% with no fruit damage detectable (Jessup *et al.* 1993). Further research is required to achieve 100% inhibition of egg hatch.

Heat treatments for control of different species of fruit fly are under development for grapefruit (Sharp 1993 in Florida; Mangan and Ingle 1994 in Texas) and for grapefruit and 'Valencia' oranges (J.W. Armstrong, USDA-ARS Hilo, pers. comm. 1993 in Hawaii). Citrus phytotoxicity as a result of heat treatment has been previously reported (Houck 1967).

Heat at 49 ºC for 20 minutes was effective in killing mealybugs (*Planococcus citri* and *Pseudococcus odermatti*) and other arthropods tested found externally on limes, or under the calyx (Gould and McGuire 2000). Treatment at 49 ºC for 20 min did not significantly affect quality when treated fruit were compared with untreated control fruit. .

There may also be opportunities for pest control by genetically *inducing resistance* in citrus to pests; adding *coatings* to the surface of the fruit (in combination with dimethoate insecticide or heat) which reduce the ability of the internal atmosphere of the fruit to sustain pests (J.D. Hansen, USDA-ARS Miami, pers. comm. 1993); demonstrating *pest-free zones* and *pest-free periods*; or documenting pest reduction due to a series of control measures applied in the production of the commodity (*systems approach*).

Previous research at the University of California (Riverside) showed *high pressure water* washes scale insects and Fuller's rose weevil eggs off citrus, but the treatment is unlikely to be acceptable to regulatory agencies as a quarantine treatment. Petracek and Kelsey (1995) measured a wound ethylene response to excessive water pressure, suggesting that there may be a loss of shelf-life of citrus if the recommended pressures are exceeded.

7.8.5 Cucurbits

Cucurbits include different varieties of cucumbers, melons and squash. For some developing countries, cucurbit production is very important for the national economy. Cucurbits are infested by a wide range of quarantine pests, particularly fruit fly, various Lepidoptera, aphids and thrips.

7.8.5.1 Existing alternatives

Most cucurbits are not fumigated with MB but are imported after inspection and certification. However, watermelon exported from Tonga to New Zealand is the only example of an inter-governmental agreement on *systems approach*, based on culling infested fruit in the field followed by fumigation with MB.

Some countries such as the United States and Japan accept imports of cucurbits only from pest-free zones. Japan accepts melon from Hsingchiang region in China as this is a *pest-free zone* for melon fly (Anon 1988a) and squash from Tasmania as this is a *pest-free zone* for Queensland and Mediterranean fruit flies (Anon 1989a). The USA accepts *vapour heat* sufficient to raise the fruit centre temperature to 44.4°C and held at this temperature for 8.75 hours as an approved quarantine treatment for controlling *Ceratitis capitata*, *Bactrocera dorsalis* and *B. cucurbitae* in eggplant, squash and zucchini (Anon 2002f). Japan accepts squash, melon and cucumber from the Netherlands as free of Mediterranean fruit fly (*host freedom*) (Anon 1993a). Bitter cucumber and netted melon shipments from Okinawa to mainland Japan are acceptable after vapour *heat* treatment for 30 minutes at 43 - 46°C to control melon fly (Anon 1987b, Anon 1989b).

Fiji developed a forced hot-air quarantine treatment for eggplant that was approved by New Zealand in 1997. New Zealand MAF has approved a forced hot-air quarantine treatment for control of fruit flies in papaya, eggplant and mango exported from Fiji to New Zealand (Anon 1997c).

7.8.5.2 Potential alternatives

Some cucurbits such as cucumber and squash are tolerant to *heat* (water or moist air) particularly if pre-conditioned to a temperature slightly less than the final temperature and therefore this treatment offers potential for controlling fruit fly and Lepidoptera. Chilling injury may limit the commercial potential for fruit fly disinfestation of zucchini exposed to 45°C for 30 minutes followed by storage at 7 - 8°C for up to 11 days (Jacobi *et al.* 1996). The commercialisation of heat treatments may also be limited by the ability of insects to increase thermo-tolerance when exposed to pre-treatment heat or cold conditions. For example, Lester and Greenwood (1997) reported that 8 hours exposure to 35°C almost doubled the time for 99% mortality in *Epiphyas postvittana* larvae compared to no pre-treatment and that synthesis of heat shock proteins was associated with this increase in thermo-tolerance. In the future, the conditions necessary to induce thermotolerance is essential to optimise heat treatments used for insect disinfestation and disease control (Paull and McDonald 1994).

It may be possible to develop a *systems approach* for cucurbits since some are not hosts to some fruit fly species and *pest-free zones* may be possible for cucurbits potentially infested by melon fly in South American produce imported by the United States. The shelf-life of cucumber is extended by *shrink wrap films* and the potential for controlling insects using this method requires further investigation (Shetty *et al.* 1989, Jang 1990).

7.8.6 Cut flowers and ornamentals

Disinfestation of quarantine pests on cut flowers is particularly problematic as they are susceptible to damage, there are many species involved and they are traded globally between many regions and countries.

Cut flowers such as roses, carnations, chrysanthemums, bird-of-paradise and orchids are economically important as exports from a number of countries including many Article 5(1) countries. Ornamental exports include deciduous woody plants, evergreens and cycads that are also economically important as exports.

Cut flowers and ornamentals are infested by a wide range of pests including external feeders, Lepidoptera, thrips, aphids, mites and scale insects. Live pests intercepted on cut flowers and ornamentals on arrival are typically fumigated with MB (Anon 2002f). The dosage varies with temperature, target pest and in the case of ornamentals the physiological state of the plant e.g. dormancy. MB fumigation often reduces vase life of ornamentals, and alternatives to Mb are being actively sought because of this effect.

7.8.6.1 Existing alternatives

MB is damaging to many types of cut flowers and the most common alternative to MB is *pre-clearance inspection* e.g. Colombia, the Netherlands and possibly Korea in the future. A treatment is only required if pests are detected, or if no treatment is available the consignment is prevented from being exported.

Aerosol formulations of insecticide chemicals (e.g. Hortigas® containing dichlorvos) and natural products (e.g. Permigas® containing permethrin) are used on cut-flower exports from New Zealand to Japan and from Hawaii to the mainland USA. They are not as effective as fumigants in penetrating flowers and relatively longer exposure periods of 3 - 16 hours are often required to obtain efficacious results (Hara 1994).

Insecticidal dip is one of the most common post-harvest treatments for cut flowers (Hara 1994) and likely to become even more widespread as an alternative to MB in the future. Hawaii and Thailand dip cut flowers in a dilute insecticide solution, such as malathion, to control thrips and other pests. The USDA-APHIS approves the use of a chemical dip (for about a 30 second immersion) in lieu of fumigation for those plants known to be intolerant of fumigants (Anon 2002f). USDA-APHIS has also approved a *high-pressure water* spray for *Succinea horticola* snails followed by a dilute carbaryl insecticide dip, or hand-removal of the pests where practical followed by immersion in a malathion-carbaryl *dip* if necessary (Anon 2002f).

MAFF-Japan has approved a *combination fumigation* as a quarantine treatment for imported cut flowers that consists of MB (14 g m^{-3}) plus hydrogen phosphide (3 g m^{-3}) plus CO_2 (5%) for 4 hours at 15 ºC or for 3 hours at 20 ºC. This treatment achieved 100% mortality of several cut-flower pests without damage to several cultivars of chrysanthemum and orchids (Kawakami 1999).

7.8.6.2 Potential alternatives

Some flowers and ornamentals are fumigated with *hydrogen cyanide* to control aphids, thrips and whitefly, but the treatment can be detrimental to some flowers such as gerbera that have a high moisture content. *Hydrogen cyanide* fumigation is no longer registered by the US-EPA as an insecticide fumigant, despite it being suitable for disinfestation of some pests from cut flowers and foliage from Hawaii (Hansen *et al.* 1991).

Irradiation is being investigated further for cut flowers and their pests in several countries including the Netherlands, New Zealand, Japan, Malaysia, Philippines and Thailand. This process has the advantage of being rapid and completely effective by arresting the development of pests and preventing reproduction. Sealed packages can be treated effectively under packed conditions with irradiation, in contrast to fumigants that are typically applied to unpacked product to improve penetration. A recent review of cut-flower irradiation (Hayashi *et al.* 1998) listed carnation, Alstromeria, Gladiolus, tulip, statice, stock, Dendrobium, prairie gentian, Oncidium, Campanula, Gloriosa, fern, Gypsophila, freesia, Lobelia, Triteleia and Gerbera as tolerant to electron beam irradiation at 400 Gy while Chrysanthemum, rose, lily, calla, Anthurium, sweet pea and iris as intolerant (Kawakami 1999).

Irradiation at 400 Gy inhibited hatching, larval growth, pupation, adult emergence and/or oviposition and sterilised adults of two-spotted spider mites, leaf-miners, mealybugs, cutworms and thrips. Although the disinfestation dosage is lower than the tolerance of cut flowers, the difference between the two dosages is not large enough to permit commercial, low penetration irradiation as the Maximum-Minimum ratio would exceed the cut-flower tolerance. X-rays would be preferable as they have better penetration than electron beam, but technology to irradiate products with X-rays for long periods of time has yet to be proven.

A dose of 400 Gy electron beam *irradiation* was reported to sterilise seven pest species on imports of cut flowers (Dohino *et al*. 1998). However, this dose damaged some cut-flower species (particularly chrysanthemum) and did not prevent aphids transmitting viruses. Damage to cut flowers was ameliorated to some extent by storing the flowers in preservative or sugar solutions after irradiation.

An *irradiation* dose of 250 Gy has been proposed as a suitable method for disinfestation of green scale (*Coccus viridus*) potentially found on gardenia blooms from Hawaii shipped to the mainland USA (Anon 2002a). Green scale is known to cause defoliation, reduced fruit set and loss in plant vigour.

Some *essential oils* extracted from plants were recently found to have fumigant activity at concentrations sufficient to rapidly kill pests found on cut flowers. Shaaya *et al.* (1997) reported that a 2h exposure at 10 g m^{-3} of unspecified plant extracts was sufficient to obtain 100% mortality of whitefly, and 4h at 20 g m^{-3} sufficient to obtain 100% mortality of thrips. Further research is required to determine the commercial potential of these extracts as quarantine disinfestation treatments.

Aerosol formulations of insecticide chemicals and natural products are under investigation in Thailand and other countries. Results to date show the formulations lack penetration into the commodity and therefore do not always kill leafminers and mites. *Fluvalinate* (a synthetic pyrethroid) is registered for use on cut flowers in the USA and its use has been recommended for tropical foliage plants imported into the USA (Osborne 1986).

Controlled atmospheres using for example CO_2 at 0 - 1°C for one week is promising for protea flowers, but the requirement for relatively long treatment times makes CA more suited to sea transport and many tropical flowers are subject to chilling injury (Hara 1994).

Fumigation with *phosphine* shows potential for quarantine treatment of live plants as Chrysanthemum and poinsettia cuttings were not damaged by concentrations and exposure periods that are known to be insecticidal to some plant pests (McDonald and Mills 1995).

A *combination fumigation* treatment of carbon dioxide (5%) MB (10g m^{-3}) and phosphine (3 g m^{-3}) at 15°C for 4 hours was 100% effective in killing 7 species of pests (Kanazawa spider mite, two-spotted spider mite, *Thrips palmi*, greenhouse whitefly, greenhouse peach aphid, cotton aphid, Japanese mealybug and cabbage moth) on cut flowers (Kawakami *et al.* 1996). Fumigation using chlorpyrifos-impregnated bags has been shown to kill ants and thrips on flowers (Hara 1994) but this use has not been registered in the USA.

Fumigation using phosphine in CO_2 (called ECO_2FUME) can be used on a wide variety of products including plant cuttings (Sloane Group 1996, McDonald and Mills 1995, Mueller 1996, Mueller *et al.* 1997). Regulatory data has been submitted in support US-EPA registration of ECO_2FUME to allow its potential to be evaluated as a disinfestation treatment for citrus, vegetables and other products that are routinely cool stored. On-site generation of phosphine in CO_2 using a Turbo Horn Generator (Anon 1996f) has also been developed as an alternative to pre-mixed cylinders of ECO_2FUME at a cost that is only marginally more than MB fumigation (EPA 1997a).

Vapour heat treatment shows promise as a disinfestation treatment for tropical cut flowers and foliage (Hansen *et al.* 1992). Magnolia white scale *Pseudaulacaspis cockerels* on 'Bird of Paradise' were controlled using 49°C water immersion for 10 minutes. Previous heat treatment research has been accepted by CDFA as efficacious against this scale species. Commercial shippers in Hawaii have adopted the hot air and hot water treatments for producing pest-free, high quality flowers for export (Hara 1997).

Warm water immersion of Cape jasmine, a popular conservatory plant from Hawaii exported to the mainland USA, for 10 minutes at 49°C disinfested all stages of green scale (*Coccus viridis*) (Hara *et al.* 1994). This treatment has not been accepted by USDA-APHIS as the Probit 9 quarantine security has not been demonstrated. However, the very low incidence of any live pests as a result of the treatment has avoided the need for treatment on arrival and is therefore commercially justified. Cape jasmine, *Anthurium*, *Cord line*, *Dracaena* , *Gardenia* and *Plumier* root and shoot development was stimulated when 0.8% IBA growth stimulant was added to this *heat* treatment. The vase life and quality of most species of *Helicon* were not detrimental or improved by hot water at 49°C for 12 minutes. Immersion of red ginger flowers (*Alpinia purpurata*) in 6-benzylamino purine after treatment further extended the vase life.

A double *insecticide dip* for 3 minutes each time with a 2 hour wait period between immersions in the dilute insecticide solution proved more effective in killing thrips species on orchids in Hawaii than a single immersion (Hata *et al.* 1993). The first dip caused pest excitability, restlessness and withdrawal from cracks and crevices on the flowers. Thrips then became more directly exposed to the second immersion. This is particularly important for chemical dips as their efficacy depends on contact with the pest which can be difficult when certain pests occur in tight cracks.

Another benefit of using insecticidal dips was reduced pesticide use in the field which is important for growers controlling pests that show resistance to a range of chemicals. Insecticides used post-harvest should differ from those used pre-harvest as a safeguard for minimising survival of pests after insecticide dipping. Some chemicals are phytotoxic to flowers and foliage leading to reduced shelf life and therefore care must be exercised in selection of the disinfestation materials.

Similarly, a post-harvest *insecticidal dip* was only 100% effective if pre-harvest pesticides reduced mealybug field populations to <6%; banana aphid infestations to <33%; and cotton aphid infestations to <70% (Hata *et al.* 1992).

Synthetic pyrethroids which have repellant activity as *fumigants* act as protectants of flowers and foliage and are especially effective in combination with insecticidal soap (Hara 1994).

A *systems approach* consisting of field management combined with post-harvest insecticide dip reduced the interception incidence of aphids, mealybug, thrips, earwigs and ants on red ginger exported from Hawaii to the mainland USA (Hara 1994). Cut flowers exported to Japan following the same procedures also show a similar reduction in interceptions of pests. This may lead MAFF-Japan to classify such consignments as 'low risk' once the very low incidence of live pests has been verified for an acceptable period of time. However, effective and consistent field pest management procedures are required to obtain this level of quarantine security.

A *systems approach* has been proposed as a suitable method for ensuring green scale (*Coccus viridis*) potentially found on gardenia blooms from Hawaii is not shipped to the mainland USA (Anon 2002a). The systems approach would be based on initial and final inspections of the production area immediately prior to export, and a border zone free of host plants surrounding the production area.

Cut flowers were considered likely to tolerate a disinfestation *CA* treatment for two-spotted spider mite (*Tetranychus urticae*) consisting of 5.5 days under 95% CO_2 in air at 0°C and a *combination treatment* consisting of a 1 day 'shock' treatment in 95% CO_2 or 0.125% O_2 at 20°C followed by 18 days in air at 0°C (Zhou and Mitcham 1997).

Advantages and disadvantages of disinfestation treatments and procedures for quarantine security of floriculture crops are summarised by Hara (1994). A particular concern is that insecticidal dips may not reach all pests, giving a preference for other treatments, such as fumigation or heat treatments, from the quarantine point of view.

7.8.7 Grapes

The main pests of quarantine concern on grapes are fruit flies, Lepidoptera, mealybug and mites.

The USDA-APHIS accepts *cold treatment* from 30 countries for control of vine moth *Lobesia botrana* and other insects in grapes providing the treatment is combined with MB fumigation. Grape exports to the United States from Chile are accepted from a Mediterranean fruit fly-free zone provided they are also fumigated with MB to control the mite *Brevipalpis chilensis*. Alternatives to MB for treatment of grapes remain a very high priority to Chilean exporters for grapes exported from Chile to the USA. US grape exports are only treated with MB on entry to other countries if pests of concern are intercepted.

7.8.7.1 Existing alternatives

Japan accepts 12 days *cold treatment* at 0.5°C for control of Mediterranean fruit fly on grapes exported from Chile (Anon 1990c). Japan also accepts that grapes from the Netherlands are free from Mediterranean fruit fly (*area freedom*) (Anon 1993a).

7.8.7.2 Potential alternatives

In-storage fumigation with *sulphur dioxide* (routinely applied for fungal control) alone or combined with carbon dioxide or carbon monoxide (Vota 1957) may provide pest control, although this has received little study. Vail *et al.* (1991) reported sulphur dioxide concentrations comparable to those used in routine fumigation of grapes to control *Botrytis* killed a key insect pest in the United States. This suggests sulphur dioxide has the potential to control both fungi and insects. However, the presence of sulphur residues from sulphites, typically about 10 ppm, may limit widespread use of sulphur dioxide for disinfestation. The United States requires mandatory labelling of products containing $\geq$ 10 ppm sulphites to warn sulphite-sensitive people of their presence.

'Kyoho' grapes tolerated 24 hours *fumigation* with 3 g m^{-3} phosphine at 15°C which was shown to be an effective treatment for killing all stages of the two-spotted spider mite (Soma *et al.* 1997a). Further research is required to determine the effects of phosphine against other pests of grapes before the commercial potential of this treatment can be evaluated. For commercial application, a safe and efficient phosphine generator has been designed and tested by Teijin Chemicals Company (Tokyo). It produces 3 kg of gaseous phosphine in < 75 minutes and uses carbon dioxide gas as the carrier (F. Kawakami, MAFF-Japan, pers. comm. 1998).

Mitcham *et al.* (1995) found a CA treatment most likely to achieve quarantine security of Pacific spider mite *Tetranychus pacificus*, *Platynota stultana* (Lepidoptera: Tortricidae) and western flower thrips *Frankliniella occidentalis,* namely 12 days under 45% CO_2 + 11.5% O_2 at 0°C. Concentrations of CO_2 less than 45% did not affect the quality of the grapes. This treatment is commercially feasible as high CO_2 treatments are easier to achieve than low O_2 conditions, and 0°C is the optimum transportation temperature for grapes.

Subsequent research by Zhou and Mitcham (1998) suggested that *controlled atmosphere* disinfestation using under 45% CO_2 could be reduced using 'shock' treatments (where 'shock' is defined as short term treatments in extreme atmospheres) consisting of 65, 80 or 95% CO_2 for 1, 2 or 3 days at 0°C followed by an 18-day treatment at 0°C in air, 8% CO_2 in air or 20% CO_2 in 5% O_2.

Yokoyama *et al.* (1999) reported complete mortality of omnivorous leafroller (*Platynota stultana*) in table grapes exposed to 3-weeks *low temperature* storage + sulfur dioxide. This combination treatment could be carried out in existing packinghouse facilities and therefore has potential to be used as an alternative to MB to control pests of regulatory concern in exported table grapes.

In Japan, *Tetranychus urticae*, *T. kanzawai* and *Eotetranychus sexmaculatus* mites were controlled at 15°C by phosphine from a generator on Japanese grapes without damage to the fruit (F. Kawakami, pers. comm. 2002).

Gamma *radiation* using less than 1000 Gy shows potential for disinfestation of grapes which are damaged by greater than 1000 Gy (Bramlage and Couey 1965, Maxie *et al.* 1971). In general the response of grapes to gamma irradiation is variable (Josephson and Peterson 1983). Other potential alternatives requiring investigation are *heat* treatments and *CAs*.

Eggs and fifth instar of omnivorous leafroller (*Platynota stultana*) and adults and nymphs of onion thrips (*Thrips tabaci*) were exposed at 0-1 ºC and 5 ºC respectively (Yokoyama and Miller 2000). The results showed that exposure to 0-1 ºC for 4 weeks attained 91.2% control, which increased to 99.8% after 6 weeks. Low-temperature storage has potential to control omnivorous leafroller in table grapes and onion thrips in onions.

7.8.8 Root crops

Root crops include yams, potato, sweet potato, cassava, carrot, taro, onion, ginger and garlic. Exports are economically important for a large number of countries and particularly important to the national economies of many developing countries.

Root crops are infested by a wide range of pests including weevils, scale, beetles, thrips, mites and nematodes. Because most of these pests can be carried in soil attached to root crops, their entry without treatment is permissible only if soil is not present. Many countries permit imports of root crops, provided the soil has been removed. Currently MB is the only registered treatment for a number of these pests on shipments of garlic and yams imported into the United States and other countries.

7.8.8.1 Existing alternatives

Sweet potatoes from Okinawa were shipped to other parts of Japan after vapour *heat* treatment at 47 - 48°C for 3 hours and 10 minutes to control sweet potato weevil, West Indian potato weevil and sweet potato vine borer (Anon 1995b).

Irradiation of sweet potatoes from Florida at 165 Gy was approved by the California Department of Agriculture for control of sweet potato weevil *Cylas formicarius elegantulus* (Hallman 2001). This was the first instance of an irradiation quarantine treatment being approved and used against a non-fruit fly species in which live adults could be found by inspectors, indicating a significant acceptance of irradiation as a quarantine treatment.

7.8.8.2 Potential alternatives

Irradiation is being investigated in Malaysia for control of nematodes and scale (*Aspidiella hartii*) in ginger (Sidam *et al.* 1994). Irradiation, currently used in many countries to inhibit sprouting of many root crops, could also be considered to prevent adult pest emergence. *Irradiation* is used for disinfestation of garlic in South Africa (Mr Du Plessis, Managing Director Gammatron, South Africa, pers. comm. 1994).

Heat treatment of sweet potato is also being evaluated in Florida for control of the sweet potato weevil and the banana moth, *Opogona sacchari* (Sharp 1995). Exposure to heat in a water dip or moist air requires evaluation because the tolerance of many root crops is unknown.

Pre-shipment inspection may be possible for some root crops that are free of soil, but this will not be feasible for internal pests such as nematodes. Many of these crops can be stored for relatively long periods of time which suggests *CA* or *cold* treatments have potential for pest control. *Dipping* in dilute insecticide and planting pest *resistant varieties* may also be feasible.

7.8.9 Stonefruit

Stonefruit include peaches, plums, cherries, apricots and nectarines. Although stonefruit are infested by a large number of pests, for most countries codling moth, fruit flies, oriental fruit moth, walnut husk fly, mites and thrips are the major pests of quarantine concern.

Some countries, e.g. United States (Yokoyama *et al.* 1987), New Zealand and Canada, have developed a mandatory MB fumigation treatment for exports of cherries and nectarines to Japan.

7.8.9.1 Existing alternatives

USDA-APHIS accepts a *cold* treatment alone for some stonefruit including cherries imported from Chile, plums from Israel and apricots, peaches and plums from Morocco (Anon 2002f).

Australia has set maximum pest levels and accepts *pre-shipment certification* from New Zealand that these are not exceeded on nectarine and apricot exports. About 14 tonnes of fresh plums imported by South Africa from France were *irradiated* at 2 kGy for insect disinfestation (Mr Du Plessis, Managing Director Gammatron, South Africa, pers. comm. 1994).

New Zealand, Brazil, Colombia and Ecuador accept a *pest-free period* for walnut husk fly on peach and nectarine exports from the United States (Yokoyama *et al.* 1992, V. Yokoyama, USDA-Fresno, pers. comm. 1998).

7.8.9.2 Potential alternatives

Stonefruit tolerate low oxygen *CAs* (0.25 - 0.5% oxygen) (Kader 1985; Ke *et al.* 1994) for 8 - 40 days depending on the commodity and the temperature. *CA* combined with *heat* may damage the quality of some stonefruit cultivars (Smilanick and Fouse 1989). The potential for controlling pests under CA at a range of temperatures is currently being determined.

Previous research has shown some varieties of nectarines tolerate 24 hours exposure to *heat* using 41°C moist air to kill some thrips species (Lay-Yee and Rose 1994). Immersion of apricots in water heated from 25 – 45°C for 10 - 30 minutes damaged fruit quality, probably due to the inoculum in the water being carried into the core cavity of the fruit (Lay-Yee and Rose 1993). However, Jones and Waddell (1996) reported on research that used water at 46-50°C for less than 11 minutes to control the tydeid mite *Orthotydeus californicus.* This was considered a possible quarantine treatment suitable for disinfestation of apricot exports from New Zealand to Australia. Mclaren *et al.* (1999) reported that water at 50°C for 2 minutes removed more than 90% of adults and killed all remaining adults, larvae and eggs. It also reduced residues of iprodione and carbaryl to 14 and 24% respectively of those in untreated fruit. Hot water treatment could therefore replace existing pre-harvest field insecticide applications for thrips control on export fruit. Californian nectarines were also reported to be tolerant to four hours heating to 47.2°C, then held at this temperature for 10 minutes, then placed in cool storage. In general, nectarines showed few differences from unheated fruit and therefore this treatment shows potential as a Mediterranean fruit fly disinfestation treatment (Obenland 1997).

Neven and Drake (1998) reported that a combination of warm air and CA generated in specialised, purpose-built equipment provided control of both codling moth and western cherry fruit fly while preserving fruit quality. The treatment on sweet cherry showed potential to replace MB fumigation.

Simmons and Hansen (1998) reported complete mortality of codling moth larvae and western cherry fruit fly maggots in several cherry varieties when exposed for up to 60 minutes at 40-50ºC. Complete mortality of codling moth was obtained in treatments that lasted for 45 minutes at 45ºC and 15 minutes at 50ºC; and for western cherry fruit fly maggot in treatments that lasted for 30 minutes at 45ºC. The effect of these pesticidal treatments on fruit quality was not reported. However, 'Bing' cherries heated in moist air at 47ºC for 35 minutes and then stored at 0 ± 1ºC for less than 14 days tolerated the treatment (E. Mitcham University of California (Davis), pers. comm. 1993) which may also control codling moth (Neven 1994b). Simmons and Hansen (1999) reported that a combination of cold and a low oxygen level can induce a high mortality in codling moth larvae (*Cydia pomonella*). Temperature storage at 1.0-2.5ºC was effective for inducing mortality of codling moth larvae and *modified atmosphere* packaging lengthened sweet cherry storage life maintaining quality.

Cherries, nectarines and peaches are the most tolerant of all the stonefruit to *irradiation* and therefore this treatment offers potential for insect control. Drake (1997) and Drake and Neven (2002e) reported 600 Gy or less may be a potential quarantine treatment for 'Bing' and 'Rainier' sweet cherries. Irradiation at this dose caused some loss in firmness but no loss of green stem colour which was observed in MB-treated cherries. Irradiation up to a dose of 300 Gy was also considered suitable as a quarantine treatment for apricots and peaches as there was little loss in quality (Drake and Neven 1998b). However, some of the larvae irradiated at 300 Gy lived for 2 months following treatment (Neven and Drake 1997b) which, if intercepted on entry, could cause concern to many regulatory agencies.

Cherries are particularly tolerant of high carbon dioxide levels generated by a *modified atmosphere* treatment which may be effective for controlling pests. 'Van' cherries, stored in 38 micrometer LDPE bags for 2 days at 38°C, tolerated MAs of about 9% CO_2, 3% O_2 at 98% RH (Brown *et al.* 1998). This treatment holds promise for control of codling moth, Mediterranean fruit fly and Queensland fruit fly in Australian cherry exports.

Stonefruit were considered likely to tolerate a disinfestation *CA* treatment for the two-spotted spider mite (*Tetranychus urticae*) consisting of 5.5 days under 95% CO_2 in air at 0°C and a *combination treatment* consisting of a 1 day 'shock' treatment in 95% CO_2 or 0.125% O_2 at 20°C followed by 18 days in air at 0°C (Zhou and Mitcham 1997). *Heated plus CA* may also provide an effective disinfestation treatment. Neven and Drake (1997b) report that fruit quality was acceptable for up to 2 weeks following treatment of cherries at 45 or 47°C under 1% O_2/15% CO_2 for 45 or 25 minutes respectively. Both treatments achieved 100% mortality of codling moth.

Cherries and nectarines are largely *host-resistant* to codling moth (Vail *et al.* 1993; Curtis *et al.* 1991). Over the past 19 years in the USA, only 8 codling moth larvae in more than 700,000,000 cherries were detected by domestic USDA-APHIS inspectors (Hansen *et al.* 1997). If the pest is present, pesticides applied in the orchard together with sorting in the packhouse (*systems approach*) can achieve a level of security which should meet or exceed the requirements of plant regulatory agencies from many countries. Nectarine varieties vary in their susceptibility to field infestation levels of codling moth which suggests *host resistance* has potential (Curtis *et al.* 1991).

In a study that examined the feasibility of the *systems approach* for fresh prune exports from California, Yokoyama and Miller (1999) reported one infested fruit per 8,500 harvested. Their finding was based on prune culls taken at random in the packhouse and opened and inspected for immature insects. These results indicated that the risk of infestation of fresh prunes exports was minimal and therefore the *systems approach* offers potential replacement of MB for quarantine purposes.

7.8.10 Subtropical fruit

Subtropical fruit include avocado, cherimoya, kiwifruit, feijoa, guava, persimmon and tamarillo. Subtropical fruit can be infested with a wide range of pests, particularly mites and fruitflies. Mites intercepted on kiwifruit in Japan are liable to fumigation with MB on arrival if the mite is considered a quarantine pest.

7.8.10.1 Existing alternatives

Japan accepts kiwifruit exported from Chile after 14 days *cold treatment* at 0°C to control Mediterranean fruit fly (Anon 1991). Avocado are commercially treated with cold treatment for fruit fly disinfestation when exported from Hawaii to the mainland USA.

González (1997) reported that Chilean-grown cherimoya (*Annona cherimoya*) were damaged by MB fumigation. However, coating the fruit with wax killed *Brevipalpus chilensis* mites (probably by preventing respiration) to Probit-9 security level without fruit damage. The treatment has been approved by the USDA-APHIS.

Cherimoya (*Annona cherimoya*) can be treated with soapy water (20 seconds in one part soap to 3000 parts water) and wax (e.g. Johnsons Wax PrimaFresh® 31 Kosher fruit coating) to control the mite species *Brevipalpus chilensis* (Anon 2002f). Although the treatment was also effective on limes it was not effective on other citrus as the wax was unable to penetrate all regions of the fruit and stalk joints to suffocate mites in these areas (González 1997).

States in Australia accept that avocados from Western Australia are free of Mediterranean fruit fly (*host freedom*) provided they are packed within three days of harvest and stored at less than or equal to 10°C (De Lima 1995).

7.8.10.2 Potential alternatives

Heat treatment of persimmons up to 54°C for less than 5 minutes, or 3.8 hours at 50°C, may be potential quarantine treatments to control diapausing and non-diapausing two-spotted spider mites (Lester *et al*. 1997), leafrollers and mealybugs (Dentener *et al.* 1996), when the impact of these or similar treatments is not detrimental to persimmon quality. Similarly, guavas (*Psidium guajava*) heated for 35 minutes in water at 46.1± 0.2°C slowed softening, sweetening and color development of fruit and delayed ripening by 2 days (Whiting *et al.* 1999a). Delaying the waxing of heat-treated guavas or reconditioning them for 24 hours at 20°C before cold storage promoted normal ripening and helped to maintain the quality of heat-treated fruit.

Dentener *et al.* (1997) considered 5 hours in 47°C water followed by 40 days at 0°C an effective quarantine treatment to control *Epiphyas postvittana* and *Pseudococcus longispinus* mealybug on persimmons. Persimmons were undamaged by 20 minutes at 54°C (Lay-Yee *et al.* 1997b), and moreover, the heat reduced chilling injury (Woolf *et al.* 1997).

Leafroller and mite pests are major impediment to exports of fresh fruit from New Zealand, particularly apples and kiwifruit. Whiting *et al.* (1995; 1996) reported on a range of air or CAs (2% O_2; 5% CO_2) combined with heat (up to 40°C, Hoy and Whiting 1998) that have potential to control leafroller pests on export apples and kiwifruit. Kiwifruit where not damaged when exposed to temperatures up to 40°C in air for as long as 10 hours followed by cooling in ambient water or air and storage for 8 weeks (Lay-Yee and Whiting 1996). Kiwifruit tolerated shorter treatments at elevated temperature under the CA.

Wax coating is being considered as a quarantine treatment for controlling *Brevipalpus phoenisis* on citrus (González 1997). It also may be possible to apply a wax formulation to grapes to kill *B. chilensis*, an important quarantine pest that results in most Chilean grapes being fumigated with MB on arrival in the United States.

Freshly-harvested 'Fuyu' persimmons treated in insecticidal atmospheres at 20°C for 3, 5, or 7 days showed slight injury but not sufficient to prevent further consideration of these as a quarantine treatment (Mitcham *et al.* 1997a). The insecticidal atmospheres were 0.25% O_2; 0.25% O_2 + 40% CO_2; or air + 40% CO_2.

The LT99s for diapause and non-diapause two-spotted spider mites (*Tetranychus urticae*) on Hayward kiwifruit were 5.4+/-0.1 hours and 8.1+/-0.3 hours respectively when exposed to 0.4% O_2 + 20% CO_2 at 40°C (Lay-Yee and Whiting 1996). The kiwifruit, subjected to 10 hours of these conditions, hydrocooled immediately after treatment and then stored for 8 weeks at 0°C, showed no significant damage.

Navarro *et al.* (2002) showed that 2-day old eggs, first stage and third stage larvae of Mediterranean fruit fly were killed in persimmons in 6h when exposed to a *vacuum* of 50 mm Hg abs. at 30°C. The same stages were killed in less than 13h when exposed to 95% CO_2 at 38°C. Further tests are required to determine the potential of these treatments as quarantine treatments to replace MB.

7.8.11 Tropical fruit

Tropical fruit include avocado, papaya, mango, banana, litchi, pineapple, guava, longan, durian, rambutan, cherimoya, carambola, passionfruit and sapodilla. Exports are economically important for a number of countries. For some developing countries, the sale and supply of tropical fruit is very important for the national economy.

Tropical fruit are infested by a wide range of pests including internal and external feeders, Lepidoptera, mites and weevils. Fruitflies are generally the pests of quarantine concern. MB is not widely used on tropical commodities because the concentrations required to kill fruit fly typically exceed the tolerance of the commodity (Arpaia *et al.* 1992, 1993).

7.8.11.1 Existing alternatives

Mango exports to Japan potentially infested with *B. dorsalis* and *B. curcurbitae* are treated by *moist heated* air to raise the pulp temperature to 46.5°C for 30 minutes when exported from Taiwan (Anon 1982a); to 46°C for 10 minutes when exported from the Philippines (Anon 1975); and to 46.5 – 47°C for 10 - 20 minutes when exported from Thailand (Anon 1993b). Mango exports from Australia to Japan potentially infested with Queensland fruit fly or Mediterranean fruit fly must achieve a pulp temperature of 47°C for 15 minutes (Anon 1996e). *Hot-water* immersion (46.1°C for 65-90 minutes, depending on fruit weight) is a USDA-APHIS approved treatment for mangoes potentially infested with fruit fly imported from Mexico, the Caribbean and Central and South America (Yahia *et al.* 2000; Anon 2002f). This treatment is being expanded to allow efficacious treatment of *Anastrepha* spp potentially infesting mangoes larger than 700g. The US has recently approved the use of irradiation to control mango seed weevil at 300 Gy minimum dose (Anon 2002).

Papaya exported from Hawaii to Japan is treated with moist *heated air* to raise the pulp temperature to 47.2°C to control Mediterranean fruit fly, melon and oriental fruit flies (Anon 1972); to 46°C for 70 minutes to control oriental fruit fly potentially infesting papaya from the Philippines (Anon 1994b); to 45 - 46°C for 30 minutes for papaya (Anon 1986b); and to 43 - 44°C for 3 hours for mango (Anon 1987b) to control oriental fruit fly shipped to the mainland from the southern islands of Japan.

The duration and temperature requirements for mango immersed in *heated* water at 46.1°C vary from 65 - 90 minutes depending on the shape and weight of each variety. Hot water dipping is in use for fruit fly disinfestation for Australian Mangoes exported to Europe. USDA-APHIS has approved treatments of papaya with dry air to a final seed cavity temperature of 47.2°C achieved over a minimum of 2 hours (Anon 2002f).

Japan accepts 15 days *cold* treatment at 1.1°C for control of Caribbean fruit fly on carambola exported from Florida (Anon 1990a). Carambola can be *cold treated* at 1.1- 0.6°C for 12 days as a disinfestation treatment for fruit flies when exported from Hawaii to the mainland USA (Armstrong *et al.* 1995).

The *systems approach* based on *pest-free zones* and *periods*, *host resistance* and *host status* has been approved by USDA-APHIS for avocados imported from Mexico to 19 North-eastern states in the USA. Imported avocados are certified free of avocado seed weevil, avocado seed moth, avocado stem weevil, fruit fly and other ‘hitchhikers’ based on field surveys, trapping and field treatments, field sanitation, host resistance, post-harvest safeguards (e.g. tarpaulins on trucks, screened packhouses) packhouse inspection and fruit cutting, winter shipping only and port of arrival inspection (Firko 1995, Miller *et al.* 1995).

New Zealand requires bananas from Australia to be immersed in a *dimethoate* solution at 500 ppm active ingredient (a.i.) for 30 seconds at a minimum flesh temperature of 18°C; and bananas from the Philippines in *fenthion* solution at 1000 ppm a.i. (Armstrong 1994b).

Papaya are treated when slightly immature, but capable of ripening later, because research has shown they are not susceptible to fruit fly infestation at this stage (*commodity resistance*). Pineapple is not a host to fruit fly allowing most exports to occur after pre-shipment inspection. Immature banana is accepted by Japan as free from fruit flies because even though the adults will lay eggs in them, the eggs will not hatch to form mature larvae (Umeya and Yamamoto 1971). Avocado may be resistant to fruit fly attack when grown under well-irrigated conditions and harvested with the stems attached to the commodity (Armstrong *et al.* 1983).

USDA-APHIS has approved irradiation quarantine treatments for three tropical fruits from Hawaii only (Anon 2002f). These are papaya, carambola and litchi for the pests Mediterranean fruit fly, melon fly and oriental fruit fly. The schedule requires a minimum dose of 250 Gy and a maximum of 1,000 Gy with documented dose mapping for each commodity, fruit size and box configuration. Additionally, irradiated commodities are to be safeguarded after treatment to ensure that they do not become reinfested. Other crops are under consideration. Commercial irradiator operators in the United States are now using irradiation for treatment of commodity pests and diseases that were previously treated with MB. Currently, no other country has adopted irradiation as a quarantine treatment for fresh products.

A treatment of 1.1°C for 15 days has been used as a *cold* treatment allowing carambola to be shipped routinely from Florida to California (Gould 1996) and a similar schedule is being examined for carambola exported from Hawaii to the mainland USA.

Litchi imported by Japan from Taiwan (Anon 1980) and China (Anon 1994a) are commercially treated with a *combination* of *vapour heat* and *cold treatment* to control oriental fruit fly.

7.8.11.2 Potential alternatives

Non-chemical options for disinfestation of tropical fruits has been summarised by Heather (1994b) and Shellie and Mangan (1994). Jacobi *et al.* (2001) reviewed the methods used to *heat* treat mango for insect disinfestation, including the physiological effects of heat treatments on mango, particularly pre-treatment conditioning and hot water treatments.

Heat (as immersion in water) has been considered for controlling some species of fruit flies in banana, guava (Gould and Sharp 1992), carambola (Sharp and Hallman 1992), mango (Sharp 1992), papaya (for the papaya fruit fly, *Toxotrypana curvicauda,* found from Mexico to Brazil; Gould 1995), and for white peach scale in Hawaii (*Pseudaulacaspis pentagona*) on papaya (Follett and Gabbard 1999).

First instar larvae of *Bactrocera aquilonis* were reported to be the most tolerant to immersion in water heated at 46 ºC and 48 ºC (Wallace 2001). This fruit fly is one of the common pest species of quarantine importance and must be controlled on all fruit and vegetable exports to New Zealand from the Northern Territory of Australia.

Yahia *et al.* (2000a) concluded that *heat* at 44°C and 50% RH in *CA* (0 kPa O_2 + 50 kPa CO_2), for 160 minutes or longer was effective in increasing the mortality of eggs and third instar larvae of *A. ludens* and *A. obliqua*. CA had a synergistic effect at temperatures less than 50°C, but was slightly less effective than air at higher temperatures. Yahia *et al.* (2000b) reported that mangoes ripened faster when exposed to 46°C for 0, 60 and 90 minutes but overall marketability was not affected. Grove *et al.* (1998) reported that South African mango infested with Mediterranean (*Ceratitis capitata*), Natal (*Ceratitis rosa*) and Maroela (*Ceratitis cosyra*) fruit flies were all killed by 70 minutes at 46.1 – 46.7°C. This treatment showed promise as a quarantine treatment. A *combination treatment* consisting of CA (no oxygen and 50% carbon dioxide) for 160 minutes at 40 - 49°C was found to give 100% mortality of eggs and first instar larvae of *Anastrepha obliqua* and *A. ludens* in mangoes (Ortega-Zaleta *et al.* 2000).

For litchi, a confirmatory test using 100,000 Mediterranean fruit fly larvae, the most resistant stage and species of fruit fly found on litchi in Hawaii, showed that, at the holding temperature of 1.1°C, quarantine security (equivalent to Probit 9) was only possible after 16 days at this temperature, but 99.8564% mortality was achievable after only 12 days (Phillips *et al.* 1997). If a level of security less than Probit 9 was acceptable for tephritids in litchi, a suitable cold treatment could be developed that was not damaging to litchi fruit quality.

The germ plasm of avocado has been screened for resistance to the Caribbean fruit fly using caged adults on fruit and observing the development of eggs (J.D. Hansen, USDA-ARS Miami, pers. comm. 1993) with a view to using *commodity resistance* as a phytosanitary measure.

Food Authority Australia New Zealand has proposed a new standard allowing irradiation of tropical fruit to control quarantine pests.

USDA-APHIS published a final rule establishing phytosanitary requirements allowing the use of irradiation treatments for imported fruits and vegetables infested with 11 species of fruit fly and/or mango seed weevil (USDA 2002). The key elements of the rule address critical control points including irradiation doses and safeguarding after treatment. The treatment is based on the pest requirements rather than on the commodity. For further details, refer to Section 7.6.1.2.

Studies were undertaken to determine whether *irradiation* treatment at 250 Gy, an accepted treatment for disinfestations of fruit flies in sapindaceous fruits from Hawaii, would also disinfest fruit of two species of *Cryptophlebia* (Follett and Robert 2000). *Cryptophlebia illepida* was determined to be more tolerant of irradiation than *C. ombrodelta*. This research showed that in the large scale tests, when 11,256 late instars were irradiated with a target dose of 250 Gy, 951 pupated (8.4%) and non eclosed as adults. Within the pupal stage, tolerance increased with age, 7- to 8–d old pupae (the oldest pupae tested) treated with an irradiation dose of 125 Gy produced viable offspring, whereas those treated with a dose of 250 Gy produced no viable offspring. Irradiation of actively ovipositing adult females resulted in no subsequent viable eggs. Therefore, the irradiation quarantine treatment of a minimum absorbed dose of 250 Gy approved for Hawaii fruits will effectively disinfest fruit of any *Cryptophebia* in addition to fruit flies.

An irradiation dose of 300 Gy or less, or 15 days at 1.1°C, was considered to have potential as quarantine treatments for lychee shipped from Florida to California to control Caribbean fruit fly *A. suspensa* (McGuire 1997b).

Control (sterility) of mango seed weevil (*Sternochaetus mangiferae*) was achieved with 300 Gy of *irradiation* (ICGFI 1994).

Film wraps have been investigated as a method to control fruit fly on papaya and mango exports (Jang 1990). Experiments in Florida have shown Caribbean fruit fly are killed in grapefruit coated with NatureSeal® prior to *heat* treatments for 60 minutes at 48°C and experiments are continuing on other fruit (guava, carambola and mango) and other treatments such as *cold* storage, *irradiation* and *insecticides* (Hallman *et al.* 1994).

7.8.12 Vegetables

Vegetables include green pod (e.g. long beans, french beans, peas) asparagus, broccoli, brussels sprouts; fruit-vegetables such as tomatoes; peppers; and leafy vegetables such as cabbage, cauliflower, lettuce and spinach. Exports are economically important for a large number of countries and particularly important to the national economies of many developing countries.

Vegetables are infested by a wide range of pests, including fruit fly, weevils, beetles, Lepidoptera, thrips, aphids and bugs. MB fumigation is the predominant treatment when a number of these pests are detected alive on shipments imported into many countries. Some vegetables are sensitive to MB fumigation (Spitler *et al.* 1985).

7.8.12.1 Existing alternatives

Most imports currently rely on *inspection* and release to the market if no live pests are intercepted. Asparagus is fumigated with MB in Japan for control of Lepidoptera and mites and with *hydrogen cyanide* when live thrips and aphids are intercepted. Sweet peppers from Okinawa are shipped to other parts of Japan after a *vapour heat treatment* to control melon fly which used to infest this island (Anon 1982b).

Tomatoes exported from Australia to New Zealand are immersed in a dimethoate *chemical dip* for control of Queensland fruit fly prior to export (Heather *et al.* 1987). Recently, New Zealand approved the *systems approach* for preventing the establishment of Queensland fruit fly in New Zealand (NAPPO 2002). The systems approach for this pest control includes documentation, grower registration, an audit to confirm the efficacy of the field treatment, postharvest chemical dipping, post-treatment security and inspection in New Zealand for compliance. The bulk of the exports also occur during New Zealand's winter when conditions would be too cold for fruit fly establishment.

Moist heated air sufficient to raise the fruit centre temperature to 44.4°C for 8.75 hours is an approved quarantine treatment for controlling *Ceratitis capitata*, *Bactrocera dorsalis* and *B. cucurbitae* in sweet pepper, eggplant, zucchini, squash and tomato imported into the United States (Anon 2002f). Japan accepts bell pepper, tomatoes and eggplant from the Netherlands as free of Mediterranean fruit fly (*host freedom*) (Anon 1993a).

A *heat* (steam) treatment of potato farm equipment was approved as a quarantine treatment for golden nematode (Anon 2002h), based on the work of Brodie *et al.* (2002). Compared to MB treatment, steam took much less time (1 hour instead of 24 - 48h), required fewer safety precautions and was expected to be more economical in the long term.

Similarly, *CA* cold storage conditions developed to maintain the quality of vegetables transported in containers from the mainland United States to Guam by the United States military were observed to kill non-quarantine pests such as aphids and thrips (Gay *et al.* 1994) and therefore could be considered as a pre-shipment treatment.

7.8.12.2 Potential alternatives

Methyl or ethyl formate *fumigants* may control pests on leafy vegetables (Spitler *et al.* 1985). Unfortunately, effective concentrations were close to the flashpoint of the fumigants (Aharoni *et al.* 1979; Stewart and Mon 1984). This risk may have been reduced by the ethyl formate in CO_2 formulation currently under test. Further research is required to define the tolerance of the pests and commodities to these natural plant products. Environmental and/or health considerations may restrict registration of these and other biocides.

Heat treatment (vapour or dip) may be feasible for some vegetables (e.g. tomato, green pod vegetables) and pests e.g. thrips. Research is required to determine the commodity and pest tolerance.

Tomatoes are currently treated commercially with *irradiation* (Corrigan 1993) a treatment that also appears feasible for asparagus (Markakis and Nicholas 1972). Most leafy vegetables undergo tissue damage at doses of irradiation less than those required to kill pests (Markakis and Nicholas 1972).

Cold treatment may control tropical pests such as fruit fly in tomatoes, particularly if they are picked immature (but capable of ripening under the specific conditions) when they are more tolerant to cold storage.

Cabbages are exported to Japan from New Zealand under in-transit *CA* conditions to maintain quality and this treatment may have potential for controlling pests.

Preshipment inspection of lettuce exported from the United States to Japan is under consideration (F. Kawakami *pers. comm*. 2002).

A postharvest *dimethoate drench* of 400 g m^{-3} applied through a packing-line spray achieved >99.99% control of Queensland fruit fly, *Bactrocera tryoni*, infesting capsicum (Heather *et al.* 1999). There were no survivors in confirmatory tests on capsicums containing 77,130 eggs, the most tolerant life stage. This method was considered suitable as a quarantine treatment for disinfestation of fruit fly in capsicum.

Vacuum treatment at > 10°C for 30 minutes with 1-4% CO_2 or 100% N_2 caused high mortality of lettuce and potato aphid, but not leafminer larvae and pupae, without detriment to the visual quality of iceberg lettuce (Liu 2002).

7.9 Existing and Potential Alternatives for QPS Treatment of Durable Commodities, Ships and Vehicles

A wide variety of alternatives to MB are available for QPS disinfestation of durable commodities, ships and vehicles, museum artefacts and miscellaneous uses. The principal alternatives in use for durables are phosphine, heat, cold and contact pesticides; for wood products, they are sulphuryl fluoride, chemical wood preservatives and heat. The choice of alternative is dependent on the item to be treated, the situation in which the treatment is required, the accepted level of risk, the speed of action required and the cost. Some alternatives such as some fumigants or heat may be implemented as stand alone treatments to replace MB in certain situations. In general, however, the level of risk may be brought to an acceptable level by combining two or more alternatives. A treatment based on a combination of measures may be optimal in many situations.

Within each commodity group, alternative treatments discussed in this Section have been *italicised* in order to highlight their use with particular commodities.

7.9.1 Bulbs

Bulbs include tulip, narcissus, lily, gladiolus and garlic. Some bulbs e.g. narcissi, are infested by dry bulb mite, bulb mite and tulip bulb aphid, although these are often difficult to detect.

Most bulbs are currently undergo *fumigation* in the United States and other countries with MB, the rate depending on whether the pest is an internal or a surface feeder.

7.9.1.1 Existing alternatives

USDA-APHIS accepts a 1 hour 43.3 - 43.9°C hot water immersion of narcissus bulbs to control *Steneotarsonemus laticeps* mite providing this is carried out within 1 month of the normal harvest date to avoid bud injury (Anon 2002f).

In Japan, bulbs infested with aphids and thrips are fumigated with hydrogen cyanide. Narcissi infested with narcissus bulb fly and thrips are dipped in hot water for 1.5 - 2 hours at 44°C.

7.9.1.2 Potential alternatives

Eggs and fifth instars of omnivorous leafroller (*Platynota stultana*) and adults and nymphs of onion thrips (*Thrips tabaci*) were exposed at 0-1 ºC and 5 ºC respectively (Yokoyama and Miller 2000). The results showed that exposure to 0-1 ºC for 4 weeks achieved 91.2% control which increased to 99.8% after 6 weeks. Low-temperature storage has the potential to control onion thrips in onions.

Lillies infested with nematodes may be dipped in a dilute *insecticide dip* (e.g. methomyl) or for tulips infested with tulip bulb mite, in an emulsion of pirimiphos-methyl. Two-spotted spider mites and aphids are killed with dichlorvos insecticide in an aerosol formulation.

Finkelman *et al.* (2002) showed that 99% mortality of large narcissus fly, *Merodon eques*, a quarantine pest of narcissus bulbs, was achieved using *hermetic storage* after 34h at 30°C. Hermetic storage of three pallets of bulbs in this semi-commercial trial at this temperature resulted in 0.1% O_2 after 18h and 21% CO_2 at the end of the treatment. The treatment shows potential as a replacement for MB as a quarantine treatment.

7.9.2 Dried fruit, nuts, coffee and cocoa

Quarantine treatments may be necessary in some cases. Many of these commodities, particularly coffee and cocoa, are typically produced in developing countries and shipped to developed countries that demand a high standard of quality and total absence of infestation by pests. Field pests may require treatment to meet quarantine or phytosanitary requirements of producer or importing countries, while the stored product (storage) pests must be treated in order to avoid damage to the product as well as sometimes to meet market or regulatory standards. Losses result not only from direct damage and downgrading as a result of pest activity, but also from charges levied by importing countries where compulsory fumigations may be carried out at point of import if pest infestation is detected.

7.9.2.1 Existing alternatives

In the port of Hamburg, Germany, phosphine is typically used to disinfest imported cocoa beans. In event of failure of this treatment permission is given to use MB. The failures may be from resistance, low commodity temperatures or short exposure times.

Phosphine as a compressed gas combined with nitrogen is used at a high dosage (4 g m^{-3}) for only 2 to 3 days when importing durables into Germany (Reichmuth 2002).

7.9.2.2 Potential alternatives

Controlled atmospheres derived from an exothermic generator have been tested as a replacement for MB for disinfestation of dried figs exported from Turkey (Demarli *et al.* 1998). Complete mortality of the moth pest (*Ephestia cautella*) was achieved in 10 tonne lots treated with <1% O_2, 10-15% CO_2, balance N_2 at 25°C for 30 hours. Commodity quality was unchanged.

Phosphine as a non-QPS treatment has replaced MB in treatment for almost all the Californian walnut crop in long term storage facilities, a use previously thought not possible because of potential for taint on the nuts. Disinfestation of pests of quarantine importance for early season walnuts destined for immediate shipment to overseas markets is currently carried out using MB under vacuum. In trials to date vacuum fumigation with sulphuryl fluoride was found to be as fast and effective as MB treatment under vacuum and could replace MB for this application (Zettler and Leesch 2000).

Sulphuryl fluoride was recently granted a temporary experimental use registration by the US-EPA for use on raisins and walnuts (Jeff Welker, International Product Manager, Dow Agri-Sciences pers. comm. 2002) but treatment application in California is also dependent on approval from the California Department of Pesticide Regulation (R. Keigwin, Pesticides Registration, US-EPA pers. comm. 2002) which is under consideration. The US manufacturer reports sulphuryl fluoride registration applications are underway in other countries and laboratory bioefficacy studies are being conducted in USA, UK and Germany.

Johnson *et al.* (2001) obtained high mortality levels for thermally-tolerant navel orangeworm after exposure times of one minute or less using equipment that generated heat using *radio frequency* (RF). Similarly, Wang *et al.* (2001) achieved 78 and 100% mortality of codling moth in two and three minutes respectively. Walnuts in the shell showed no increase in peroxide values or fatty acid levels suggesting that RF may be a rapid and suitable quarantine treatment as an alternative to MB.

Bell and Conyers (2002) showed that controlled atmospheres (0.5% oxygen, 13% carbon dioxide and 86.5% nitrogen) gave 100% mortality of three stages of rice pests in 24h at 44°C; four pests of herbs and spices in less than 16h at 40°C; 6 pests of dried fruit and nuts at 38°C in less than 16h; and four pests of cocoa and coffee beans in less than 16h at 36°C. These treatments did not affect the quality of the products and therefore showed potential to replace MB for QPS treatments.

Two experiments were carried out in the field trial, each using 15m^3 capacity plastic containers termed the “GrainPro Cocoon™” or “Volcani Cubes™, specially adapted to facilitate low pressure ("vacuum cube") (Varnava 2002). The pressure in the vacuum cube was established within the range of 23 to 75 mm Hg abs. In one cube the low pressure was held for 3 days and in the second, for 7 days. In both cubes 100% mortality of all test insects was obtained suggesting this treatment could be a useful alternative to MB for QPS treatments in developing countries.

Propylene oxide (PPO) has been suggested as a possible replacement for MB for fumigation of some food products and pests, particularly those fumigated under vacuum (Griffith 1999, Isikber *et al.* 2001). PPO must be applied under vacuum for safety and efficacy reasons. The material has registration and residue tolerances for use as a sterilant for nutmeats, cocoa powder, and spices in the USA. PPO is a candidate treatment to disinfest codling moth in walnuts exported from the USA to Europe. PPO is listed by the US-EPA as a 'likely carcinogen' (Griffith 1999). In addition to PPO, *methyl iodide*, *carbonyl sulphide* and *sulphuryl fluoride* are under evaluation (Zettler and Leesch 2000).

Isikber *et al.* (2002) investigated the effects of PPO as a replacement for MB quarantine treatment for stored product pests in corn, cocoa and wheat. A *ct*-product of 96 g h m^{-3} at 100 mm Hg abs. achieved 100% mortality of all stages of *Tribolium castaneum*, *Ephestia cautella*, *Plodia interpunctella* and *Oryzaephilus surinamensis.* PPO was rapidly absorbed and desorbed from the commodities. It was less toxic than phosphine, but more toxic to insects than MB and carbonyl sulphide. Further research is required on a large scale to determine its value as a replacement for MB.

Walnuts were *irradiated* to control codling moth at a dose shown to not affect the walnut taste (Rhodes 1986). Johnson (1995) considered it technically feasible to use irradiation to disinfest codling moth in walnuts exported from the USA to Europe. Johnson and Marcotte (1999) consider it unlikely that irradiation would completely substitute for fumigation but it may be suitable as a quarantine treatment for packaged product.

Johnson and Valero (2002) showed that a *vacuum* of 33.5 mm Hg abs. at 35°C for 16 hours was sufficient to kill codling moth eggs, non-diapausing larvae and pupae but only 69% of diapausing larvae. Navel orangeworm larvae were more tolerant of the treatment but not as tolerant as diapausing codling moth larvae. This potential commercial treatment for walnuts has advantages of leaving no chemical residues or emissions and low capital expenditure and energy costs but treatment times would be longer than those for the same phytosanitary treatment using MB.

7.9.3 Grain

7.9.3.1 Existing alternatives

Phosphine is typically applied as aluminium phosphide to protect grain, or less commonly used as magnesium phosphide preparations. These decompose by the action of ambient humidity liberating the fumigant gas. Problems of slow and uncontrolled release of gas, inadequate dosage profiles and residues from formulations have driven interest in developing an external supply system for phosphine. An external supply system for phosphine consists of cylinders of this gas compressed and mixed with either CO_2 or nitrogen. Various formulations are registered in several countries including Australia, Cyprus, Germany and USA (Cytec 2000). There are also a number of phosphine generators under development, trial and use. These are based on hydrolysis of aluminum or magnesium phosphide in some form of reactor. In many designs, a stream of CO_2 is used to entrain the liberated gas to reduce its flammability (e.g. Horn 1998). Forms of these devices are in use in China for disinfestation of bulk grain and have been successfully trialled for treatment of mills in USA, empty shipholds in Canada (Fields and Jones 1999) and grain in silo bins in Australia. Where the corrosion problems associated with phosphine and its slow action can be tolerated, generators may provide an efficient alternative to MB fumigation. Target concentrations are achieved more rapidly. They avoid formulation residues and can give more controllable and consistent dosage profiles.

Some winter wheat fields in Texas were infected with Karnal bunt disease, *Tilletia indica*, in 2001. When infected grain was harvested and transferred to storage bins, the bins and grain handling equipment became infected. Once emptied, MB fumigation of contaminated storage bins requires a high dosage of MB (240 g m^{-3}) for 96 hours to meet quarantine standards. Steam heating to a point of runoff in bins also is an effective alternative to MB providing surface temperatures reach 77°C (Dowdy 2002).

The introduction of *hermetic storage* bunkers in Cyprus for grain storage system as a QPS treatment successfully protects grain against insects, rodent contamination, bird attack and losses and allows access to international markets for bulk grain (Varnava 2002). In Cyprus the combination of hermetic storage with grain aeration and good management is essential for profitable and ecologically friendly grain handling.

MAFF (Japan) authorises the use of *carbon dioxide* for control of quarantine pests in four schedules and at three different temperatures (Kawakami 1999).

7.9.3.2 Potential alternatives

In-transit treatment of some bulk durable foodstuffs with *phosphine* in ships may potentially replace some pre-shipment uses of MB. It is estimated that this in-transit treatment could replace at least 500 tonnes per annum of MB use, equivalent to 0.7% of current global consumption (C. Watson, Director Igrox Ltd UK, pers. comm. 2000). For example, in-transit phosphine could replace MB when the latter is used as a rapid disinfestant at point of export to meet official phytosanitary requirements of some importing countries. Much of this use could be in Article 5(1) countries, particularly in Thailand and Vietnam. Typical examples include shipments of rice, cassava chips and other durable foodstuffs in bulk and bags. These treatments may be conducted at the dockside, in lighters or barges prior to loading a ship, or in the ship after loading and before sailing. Phosphine could also be used to replace MB as an in-ship quarantine treatment for bulk cargo at the discharge port.

The 1996 revision of the International Maritime Organisation (IMO 1996) specifically recommends that cargoes should not be fumigated in ships with MB prior to sailing due to the risks resulting from the difficulty in ventilating the cargo effectively. Despite the recommendations of the IMO, the practice of MB fumigation in ships prior to sailing remains widespread. As an alternative to MB and for safety and efficacy reasons, *in-transit treatment with phosphine* is restricted to specially-designed bulk carriers, tanker-type vessels and other ships where the holds are gastight or can be made so (Semple and Kirenga 1997). In addition, equipment must be installed to circulate the phosphine through the cargo mass (Watson *et al.* 1999). The circulation equipment ensures that the gas penetrates throughout the load and can be aired from the load prior to unloading. In-transit treatment of quarantine pests with phosphine requires treatment acceptance by regulatory authorities, in addition to requiring appropriate vessels and equipment (Watson *et al.* 1999, IMO 1996, Semple and Kirenga 1997).

In Japan, *Sitophilus granarius*, *Callosobruchus rhodesianus* and *Ephestia cautella* as well as some other grain pests were killed using *coldstorage* at -18 ºC in 5 hours without damage to wheat, maize and soybean (Kawakami 1999). The speed of treatment and its efficacy in killing pests render cold a potential quarantine treatment.

Microwave energy is under investigation in Spain for disinfestation for rice as a QPS treatment (Sánchez-Hernández *et al.* 2002).

7.9.4 Museum artefacts

The preservation and protection of artefacts represents a broad area of interest including commercial aspects and artefacts of substantial value or of irreplaceable cultural and national significance. Many of the objects held in museums, libraries and similar repositories are subject to attack by rodent and insect pests and at high humidity by fungi. Infested materials include those made of wood, paper, leather, and skins, feathers wool and other natural fibres. Artefacts and similar objects made of organic materials are also objects of international trade and may carry pests of quarantine significance (Reichmuth 2002).

7.9.4.1 Existing alternatives

Many museums, libraries and similar repositories have installed a holding room that isolates artefacts newly introduced to museum premises but not yet on display in order to ensure that only insect-free artefacts enter the display location. This would also be a suitable QPS treatment when exporting or importing museum artefacts on loan for an exhibition. Freezing or treatment with nitrogen gas controls quarantine pests (Pinniger 1991). Emphasis is thereafter focused on minimising the risk of introducing damaging pests. In museums, longer exposure periods for pest control are not a constraint (Reichmuth 2002).

Controlled atmospheres are being increasingly used as a replacement for MB as quarantine and non-quarantine treatments for insect control in artefacts (Reichmuth 2002). The treatment may take 2 to 8 weeks in gas-tight chambers (Gilberg 1991, Reichmuth *et al.* 1992, Newton 1993, Adler *et al.* 2000). CAs with humidified nitrogen in a carefully constructed gastight enclosure, can control all stages of museum insect pests after purging to reduce oxygen contents far below 1%and holding them for up to 30 days. Atmospheres with more than 60% carbon dioxide in air are also proving to be effective replacements for MB in museums (Newton 1993).

Heat and *cold* treatments are used as quarantine treatments to disinfest artefacts, provided condensation and cracking of wood and other sensitive materials can be avoided by appropriate control of moisture (Reichmuth 2002). Exposure to –18°C can provide disinfestation of woollen artefacts from clothes moths in a few days (Brokerhof *et al.* 1993).

Strang (1992) reviewed the use of integrated pest management treatments to control pests in museum libraries and artefacts. While the majority of these applications may be for non-quarantine pests, some of these treatments may be suitable for controlling quarantine pests.

Irradiation has been effectively used to control insect and fungal problems in historical artefacts, art objects, and books and paper archives. The minimum recommended dose for pest control ranged between 0.5 kGy for insect control to 1.6 kGy for both insects and fungi (Fan *et al.* 1988).

Kidd (1999) has provided an updated review of the use of *heat in combination with controlled humidities* as well as controlled atmospheres to replace MB fumigation for the treatment of valuable artefacts.

7.9.4.2 Potential alternatives

MBTOC was not aware of tests to find further alternatives.

7.9.5 Seeds for planting

The development of quarantine programmes for seeds requires biological and ecological information about seedborne pathogens, the ability to detect their presence, knowledge about the inoculum type and its location on seeds, and effective means for control.

Table 7.2 Some nematodes transmitted by seeds

Nematodes	Seed species		Distribution
Aphelenchoides besseyi	Rice	*Oryza sativa*	Asia, America, Africa, Italy and others
A. ritzemabosi	Aster	*Callistephus sinensis*	Europe
Anguina tritici	Wheat, rye	*Triticum, Secale*	Europe, Asia
A. agrostis	Bentgrass	*Agrostis, Lolium*	Europe, USA, Australia
A. amsinckiae	-	*Amsincka*	America
A. funesta	Rye grass	*Lolium rigidum*	Australia
Subanguina chrysopogoni	Grass	*Chrysopogon fubus*	Asia
Ditylenchus angustus	Rice	*Oryza sativa*	Asia, Egypt
D. dipsaci	Oat	*Avena*	Europe
	Onion	*Allium*	Europe
	Shallot	-	Europe
	Beet	*Beta*	Europe
	Fuller's teasel	*Dipsacus fullonum*	Europe, America
	Cat's ear	*Hypochaeris radicata*	America
	Lucerne	*Medicago*	Europe, New Zealand
	Plantain	*Plantago*	America
	Dandelion	*Taraxacum officinale*	America
	Clover	*Trifolium*	Europe
	Field bean, Broad bean	*Vicia faba*	Europe, Africa, Middle East

Nematodes	Seed species		Distribution
	Carrot	*Daucus carota*	"
	Runner bean	*Phaseolus*	"
	Pea	*Pisum sativum*	"
	Buckwheat	*Fagopyrum sagittatum*	"
	Spring vetch	*Vicia sativa*	"
D. africanus	Groundnut	*Arachis hypogea*	Africa
Heterodera schachtii	Beet	*Beta*	Europe
Rhadinaphelenchus cocophilus	Coconut	*Cocos nucifera*	Tropical America

From Bacci Del Bene and Cancellara (1973) and Caubel (1983)

Seed treatments to control seedborne inoculum can be based on chemical, physical, mechanical and biological practices. Chemical and physical methods will be primary considerations for quarantine issues. Although the complete elimination of seedborne inoculum is desirable for quarantine purposes, in practice seed treatments often do not provide this level of control. Few examples exist where seed treatments have reliably and consistently eradicated seedborne inoculum (Fraedrich 2002).

Several nematode genera are known to be seed-borne (Caubel 1983). The most important in agriculture are *Anguina, Aphelenchoides* and *Ditylenchus* (Bacci Del Bene and Cancellara 1973). Many crop species may be infested, including rice, wheat, leguminous plants and onions. Table 7.2 lists some of the nematodes transmitted on seeds. These nematodes may be also transmitted by propagules: bulbs, stolons, and cuttings.

The increase in international exchanges of seed increases the risk of dispersal of seed-borne nematodes. Regulations and certification schemes are required to improve the chances of limiting the dispersal of these important plant pests.

MB is a standard technique for destroying dormant nematodes in seed lots. There is usually little effect on seed germination after treatment under controlled conditions (Strong and Lindgren 1961). Fumigation of seeds with MB is used routinely as a quarantine treatment.

Developing countries are particularly dependent upon the use of MB for quarantine treatments of seed lots because imports are often only permitted if fumigated in the country of origin or at ports of entry. As some species are associated with plant debris, thorough cleaning reduces the chance of spreading infestation.

7.9.5.1 Existing alternatives

MBTOC was unaware of any approved alternative to MB for controlling nematodes in seeds for planting.

Fungicides have been used routinely to control seedborne pathogens and are often the cheapest and most effective means for control. Highly selective systemic fungicides have proved to be most useful for the eradication of inoculum in seeds. Fungicides can be used in combination with carriers such as acetone, dimethyl sulphoxide, or dichloromethane to facilitate the infusion of the fungicide into seeds to eliminate fungi located internally. Disinfectants such as sodium hypochlorite and hydrogen peroxide have proved useful for elimination of inoculum associated with the seed coats of conifer species (Fraedrich 2002).

7.9.5.2 Potential alternatives

Phosphine is not typically effective against seed-infesting nematodes. However, experimental applications of phosphine were effective in controlling nematodes in water suspension (Rout 1966) suggesting that phosphine may be a suitable disinfestation treatment.

Phosphine may also be used in combination with soaking in pesticides. Prasad (1992) eliminated *Aphelenchoides besseyi* nematodes by soaking rice seeds in a solution of mancozeb and monocrotophos followed by fumigation with phosphine at the high dosage of 9.3 g m^{-3}.

A. besseyi was controlled by soaking rice in aqueous solutions of systemic organophosphorus compounds without adverse effects on the seeds (Fortuner and Orton Williams 1975).

Heat treatments have been used to control certain seedborne pathogens while maintaining seed viability. Various methods have been used to apply heat treatment, including hot water, hot air, aerated steam and radiation. These practices have been used to eradicate seedborne fungal pathogens of some agricultural crops, but results are variable. Some attempts have been made to use hot water treatments for control of pathogens in seeds of tree species, but results hitherto have not been as good as those with chemical control practices (Fraedrich 2002). Some of these treatments may also be applicable for controlling seedborne nematodes.

7.9.6 Ships, freight containers and other vehicles

7.9.6.1 Existing alternatives

Phosphine is used as a pre-shipment treatment on empty ship holds in Canada for controlling both insects and rodents prior to loading grain. *Hydrogen cyanide* (HCN), together with rodenticides and traps, is used for controlling rodents in Singapore and France. On occasions rodent control could be considered as a QPS treatment as the Protocol definitions include disinfestation for human health reasons, but the treatment would need to be authorised by a government health authority.

HCN is also used in empty vessels alone where there is no water in the bilges. HCN has some advantages in the control of rodents because it rapidly kills them and their parasites, principally fleas which can carry pathogens dangerous for human health. Availability of HCN may be limited by its extreme acute toxicity and regulations on its transportation and handling. Most countries have discontinued registration of HCN for health and safety reasons. Fumigation of freight containers can be carried out either before (pre-shipment) or after transport (post-shipment). All containers under fumigation are classified as Dangerous Goods under the International Maritime Organisation Dangerous Goods Code, the provisions of which allow *phosphine* fumigation in transit, which may replace some pre-shipment fumigations with MB.

Sulphuryl fluoride is also permitted for disinfesting freight containers where this gas is available.

Some containerised cargo in transit is fumigated with *carbon dioxide* as an alternative to MB before shipment from Australia, following the methods described by Banks (1988). Linde AG in Europe has also used high levels of carbon dioxide for up to 12 hours on aircraft to control rodents (J. Banks, pers. comm. 2002).

7.9.6.2 Potential alternatives

Phosphine may be suitable as an alternative to MB for treatment of empty ships and barges for rodent and insect control prior to loading commodity (Fields and Jones 1999). Some developing countries currently use MB for this purpose. While phosphine is rapidly lethal to rodents, its slow action against insect pests, and consequent demurrage costs, may limit its usefulness. Where ships contain cargo, in-transit fumigation with phosphine or modified atmosphere treatments may be feasible.

The efficacy of MB and two formulations of *phosphine* (supplied by generator or from gas cylinders) for disinfestation of empty shipholds was compared in Canada (Fields and Jones 1999, Mathews and Shaheen 1999, Cavasin *et al.* 1999). The results showed phosphine was effective in controlling several different stored product insects. Phosphine treatments required 72 hour exposure to kill lesser grain borer compared to less than 32 hours for MB, but were more rapid than MB against red flour beetle. The treatment might be considered to take too long especially under winter conditions and therefore is unlikely to be considered further as a disinfestation treatment.

Commercial vehicles and railway cars may also require treatment to meet quarantine legislation when empty and prior to loading. In some countries MB treatment is currently mandatory. Phosphine could be an alternative treatment for rail cars. Nitrogen-based controlled atmosphere treatments are being considered for quarantine rodent control between Barrow Island and mainland Australia for treatment of trucks and containers (J. Banks, pers. comm. 2002).

A preliminary test using steam was used to kill an introduced Mediterranean snail, *Cernuella cisalpina*, infesting maritime shipping containers (MilVan) resulted in 100% control when temperatures exceeded 54°C for 20 minutes (Mack and Norris unpublished data, cited in Dowdy (2002)).

The golden nematodes (*Globodera rostochiensis* and *G. pallida*) are potato pests of quarantine significance that occur in a few isolated areas of the northeastern United States and in other countries. Used farm equipment, construction equipment, and containers infected with the nematode require a very high dosage of MB treatment (240 g m^{-3} for 24 h) to meet quarantine standards. Heat treatment using steam is effective for treating golden nematode infected equipment. Brodie and Norris (2001) injected live steam into a tent containing a tractor that was contaminated with all life stages of the nematode. A one-hour treatment at temperatures above 60°C resulted in 100% mortality of all life stages. The specific treatment parameters are being developed and the alternative is being considered as a potential QPS treatment (Dowdy 2002).

7.9.7 Timber and wood products

In general, MB is important for QPS treatment of wood products and timber as it is used for:

- Disinfestation of museum objects and cultural relics in trade (see Section 7.9.4)

- Treatment of unsawn logs, traded internationally, against insect pests and some fungi;

- Quarantine treatments against specific pests, particularly the house longhorn beetle, *Hylotrupes bajulus*, and certain snails;

Logs, timber and bark products such as particle board, wood chips as well as wooden products, containers, pallets, toys and sports goods all come under either phytosanitary or quarantine regulations in international trade because of the likelihood of pest infestation. Quarantine uses of MB also exist for bambooware.

Wood products such as logs, timber, bamboo ware, packaging materials and certain manufactured wood products are treated with MB to control organisms of quarantine significance. Two major classes of pests require control: insects (Table 7.3) and fungi.

In some cases insects and fungi are considered quarantine pests. In addition, the nematode *Bursaphelenchus xylophilus* is a major quarantine pest of timber in Europe. Other pests of quarantine significance are snails. For pests that infest or infect wood or wood products, alternatives can be classified into two types of treatments: those applied directly to the product, and those treated in a confined space. Some wood inhabiting fungi which need to be controlled, usually for quarantine purposes, are: *Antroida carbonica, Ceratocystis fagacearum, Gloeophyllum sepiarium, Lentinus lepideus, Lenzites sepiaria, L. trabea, Postia placenta* and *Serpula lacrimans.*

Timber infested by the oak wilt fungus (*Ceratocystis fagacearum*) is usually fumigated with MB as an approved treatment prior to export to Europe under gas-proof sheets or in chambers at the high rate of 240 g m^{-3} (Liese and Ruetze 1985). This fungus is regarded as a particularly serious quarantine problem on logs exported to Europe. It should be noted that while there are a variety of potential substitutes, research is required to establish them as satisfactory treatments that meet the various standards stipulated by different quarantine authorities for the different pests (Lung Escarmant *et al*. 1985).

Table 7.3 Typical insect pests in logs, timber packaging materials and manufactured wood products

Scientific name		**Common name**
Acanthocinus spp.		Pine bark borers
Anoplophora glabripennis	*	Asian long horn beetle
Arixyleborus spp.		
Cerambycidea scolytidea	*	Longhorn beetle
Dentroctonus spp.	*	Book beetles
Diapus pusillimus		Walnut pinhole borer
D. quinquespiratus		
Gnathotrichus retsus		Ambrosia beetle
G. sulcatus		Ambrosia beetle
Hylastes ater		Black pine bark beetle
Hylotrupes bajulus		House long horn beetle
Ips spp.		Bark beetles
Lyctus spp.	*	Powder-post beetles
Monochamus spp.	*	Sawyer beetles
Orthotomicus suturalis		Bark beetles
Platypus spp.		Ambrosia beetles
Polygraphus subopacus		Bark beetle
Rhagium spp.		
Scolytus spp.	*	Bark beetles
Tetropium cinnamopterum		Eastern larch borer
Trypodendron lineatum		Striped ambrosia beetle
Urocerus gigas	*	Woodwasp, Sirex
Xyleborus spp.		Ambrosia beetles

*Major pests

7.9.7.1 Existing alternatives

Banks (2002) and Reichmuth (2002) recently reviewed the use of alternatives for timber.

Under water dipping of logs for plywood is a necessary process as it improves the quality of the products. However, it needs broad water area and a long exposure time. There is an approved treatment for logs to be kept immersed in water for more than 30 days in order to control pests. The upper surface of the logs above the water level is sprayed with an insecticide mixture such as dichlorvos as part of the pest management strategy. There is an approved quarantine treatment involving immersion of logs in water and treating the upper surface of the logs above the water level with an insecticide mixture (Reichmuth 2002). In the USA and Japan, a dip-diffusion treatment in a solution of borate is registered for sawn timber. Australia allows pressure impregnation of insecticidal mixtures as an alternative to MB for treatment of wooden pallets for control of *Sirex noctilio* and other wood pests. In Japan, approximately 14% of the logs imported in 1992 were treated using this technique, replacing the alternative methyl bromide treatment (Reichmuth 2002).

Timber is immersed in a 10% solution of *bifluorides* for five to ten minutes. No monitoring equipment is required and temperatures must be above freezing. This relatively inexpensive treatment is accepted in many European countries (Reichmuth 2002).

Some wooden artefacts and medicinal herbs imported from Asian-Pacific countries are commercially *irradiated* on arrival in Australia as a quarantine treatment (J. Banks pers. comm. 2002).

Heat treatment of timber against certain pests is becoming increasingly common. To some extent, the observed increase in the use of this technology is being driven by pests not normally controlled by MB e.g., pine wilt nematode in timber and timber packing in trade from USA to China or control of certain fungal pest for timber imports into USA. Heat treatments will differ depending on the pests being controlled. Heat is effective as an alternative to MB for controlling many fungal species. This will lead to different treatments for different situations, e.g. Malaysia and USA have different heat regimes for control of pests in timber. Dwinell (2002) reported that neither the APHIS-approved MB treatment for timber nor heat treatment up to 81°C killed all saprophytic fungal pathogens in imported hardwood pallets and recommended the use of seasoned, pest-free lumber at the time of manufacture. Many fungal pathogens are also very tolerant of methyl bromide.

The use of elevated temperature to manage pests in transported wood is already used for higher value wood products and kiln-dried wood (Dwinnel 2001). In wood, the lethal temperature for insects is below those found for the pine wood nematode and many wood-inhabiting fungi. The technology, such as kiln chambers for using artificial heat to season lumber, is well established.

As *heat* can eliminate both quarantine and non-quarantine pests in wood, it has been recommended by the IPPC as a Standard (ISPM No. 15) that could be approved as a viable alternative for countries that have the necessary infrastructure to carry out and document the treatment (Anon 2002). This standard specifies 56°C shall be obtained in the center of treated timber for at least 30 min. Steam heat or hot water dips are generally most suitable, but kiln drying or dry heat is suitable for sawn timber. The ISPM for timber has been temporarily suspended until a new mark for the certification of approved measures has been developed (http://193.43.36.94/cds_ippc/IPP/en/SuspendISPM15.htm) which is likely to delay implementation of the Standard until 1 June 2003 (NAPPO 2002). The continued expansion of heat for this use is likely (http://www.ars.usda.gov/is/np/mba/jan97/steam.htm). Heat treatment by steam has been shown to eradicate all tested fungi when 66°C is held at the centre of wood for 1.25 hour (Miric and Willeitner 1990, Newbill and Morrell 1991, but see also Dwinell, 2002).

USDA-APHIS (Anon 2001b) permits solid wood packing material imported from China and other countries to be *heat* treated, *fumigated* with MB or treated with *preservatives* prior to export. The shipments must be stored after treatment to prevent re-contamination and accompanied by a phytosanitary certificate issued by the government.

The US has defined *heat treatments* and *fumigation* options for lumber and kiln dried wood potentially infested with a range of wood-boring insect pests (www.aphis.usda.gov/ppq/permits/wood/annex.html). *Debarking* of timber is practiced to a limited extent as a control measure against pests, particularly bark beetles. Debarking appears to have the potential to reduce the need for MB fumigation where bark-borne pests are the objects of the treatment. Debarking can be easily done for certain species of timber, but not all species.

Naito *et al.* (1999) found that seven of ten species of forest insect pests were controlled by *MITC* at 40 g m^{-3} for 24h at 15 ºC. MITC was registered in Japan for control of forest insect pests such as the pinewood nematode. Tests under sheets with import logs as a quarantine treatment were successfully carried out using 40 g m^{-3} MITC at 15°C for 24 hours (F. Kawakami, pers. comm. 2002).

Fumigation of logs using *phosphine* was effective in controlling bark beetles, wood-wasps, longhorn beetles and platypodids at a dosage of 1.2 g m^{-3} for 72h at 15 ºC or more. This schedule is registered only in the United States. The length of time required to complete treatments restricts its commercial acceptability. New developments include phosphine to treat bamboo in transit to avoid MB quarantine treatments in Japan (Reichmuth 2002).

Application of chemicals under pressure represents one method for reducing the risk of pest introduction on wood packing materials. Pressure treatment involves the application of a preservative using combinations of vacuum and pressure to “force” the chemical more deeply into the wood. Pressure treatment has been commercially available since the 1930’s and is widely used to improve the durability of wood products exposed to adverse environmental conditions. For example, nearly 360 million cubic meters of wood are pressure-treated with preservatives each year (Morrell 2001a). The chemicals used for pressure treatment are either oil- or waterborne. Waterborne preservatives are primarily inorganic metal systems that include chromated copper arsenate (CCA), copper azole, ammoniacal copper quaternary, copper citrate, and ammoniacal copper zinc arsenate. CCA is by far the most commonly used waterborne system for wood treatment and tends to leave the wood a greenish color. Boron solutions are also used to pressure treat wood in some regions of the world. This chemical is the only system in this section that does not react with the wood or otherwise become immobilized to resist leaching. Oil-based preservatives include creosote, pentachlorophenol, copper naphthenate, and copper-8-quinolinolate. In most applications, wood treated with these chemicals has an oily appearance that makes it less attractive. There are also some specialized systems used for high-value applications, such as 3-iodo-2-propynyl butylcarbamate plus chlorpyrifos, which is used to treat laminated timbers used in tropical environments where termite and fungal protection is required. Given the single-use of packing materials, lower chemical loadings may be acceptable provided they continue to prevent pest infestations. This approach might also allow the substitution of less broadly toxic preservative systems. A side benefit of reduced chemical loadings would be a lower risk of health-related problems arising from improper disposal.

7.9.7.2 Potential alternatives

Fumigation of red oak (*Quercus rubra*) with MB has been successfully used in the past to prevent accidental imports of the oak wilt fungus (*Ceratocystis fagacearum*) into Europe from the United States, and to control enzyme-mediated grey stain in oak lumber. A successful quarantine treatment for either purpose is directly correlated with the death of parenchyma cells throughout the sapwood. *Sulphuryl fluoride* was effective in killing parenchyma in log sections at treatment levels and times required to eradicate the fungus (Schmidt and Chrisopherson 1997). Methyl iodide also killed parenchyma in less time than sulphuryl fluoride. Phosphine was not effective. Further research is required to determine the potential for sulphuryl fluoride or methyl iodide to replace MB as a quarantine treatment.

Sulphuryl fluoride (SF) is considered a practical alternative to MB for many uses, particularly for quarantine fumigation applications (Woodward and Schmidt 1995). It is currently registered for use under the trade name Vikane® and is used in some European countries to control a wide range of pests including wood-destroying beetles, furniture and carpet beetles and clothes moths. SF is toxic to post-embryonic stages of insects (Kenaga 1957) but the eggs of many species are very tolerant especially at low temperatures, requiring concentrations of over 50 g m^{-3} and exposures of up to three days for complete kill (Williams and Sprenkel 1990). Eggs of *Ephestia kuehniella* at 25°C required a *ct*-product of about 1000 g h m^{-3} to prevent hatch and 800 g h m^{-3} to prevent emergence (Bell and Savvidou 1999).

Research is ongoing to evaluate the potential of *sulphuryl fluoride* for timber treatment for plant quarantine purposes (Kawakami 1999). Efforts are underway to develop treatment schedules to fumigate timber being imported into the USA, Europe and Japan to control wood-destroying beetles or fungal pathogens (Chambers and Millard 1995, Kappenberg 1998). In Japan, sulphuryl fluoride was effective in controlling forest pests only when used at above 25 ºC. However, a combination of sulphuryl fluoride and hydrogen phosphide for 24 and 48 hours at 15 ºC achieved a high level of pest mortality compared to the use of sulphuryl fluoride alone (Kawakami 1999).

Sulphuryl fluoride at 60 g m^{-3} for 48h was 100% effective in killing insects from the families Bostrichidae, Platypodidae, Ipsidae, Atractoceridae, Lyctidae and Curculionidae on timber imported by China from Côte D'Ivore (Tang *et al.* 1985). Most of the insects had not been observed in China before and could therefore have been considered quarantine pests. Research is ongoing to further evaluate the potential of sulphuryl fluoride as a quarantine treatment for timber (Schmidt and Christophersen 1997). Research showed that relatively large dosages were required to control egg stages of ambrosia beetles (*Xyloborus* spp.) (Mizobuchi *et al.* 1996, Soma *et al*. 1996). Sulphuryl fluoride is widely applied for log disinfestations. Sulphuryl fluoride may not be effective for controlling fungi such as *Ceratocystis fagacearum* (Woodward and Schmidt 1995).

Efforts are underway using SF to develop treatment schedules to fumigate timber being imported into the U.S., Europe and Japan to control wood-destroying beetles including the Asian long horn beetle or fungal pathogens (Chambers and Millard 1995). However, recent studies suggest SF treatments may not be practical under cool conditions. Tests of SF against Asian longhorn beetle developmental stages have shown survival of some stages at low temperatures even at high dosages. Even at 10°C, cold acclimated larvae require a *ct*-product in excess of 3000 g h m-3 for a quarantine level of kill with a 24-hour exposure (Barak 2002).

In laboratory tests, pinewood nematodes infesting red pine lumber (15cm×15cm×30cm) were completely controlled by *methyl isothiocyanate* (30%

MITC in CO_2) fumigation with 40 g m^{-3} for 24h or 20 g m^{-3} for 48 hours at 15 ºC at 25% loading (Soma *et al.* 2001). MITC is available in cylinders in Japan as a compressed gas. Large scale tests with this process were carried out in Japan in 2001 (F. Kawakami, pers. comm. 2002).

Oogita *et al.* (1997) found that exposure to *phosphine* of eight forest insects pests resulted in variable results and therefore phosphine alone was unlikely to be useful as a quarantine treatment.

Debarking, together with conversion to sawn timber in the country of origin, appears to have the potential to reduce a need for MB where bark-borne pests are the objects of the treatment, including quarantine treatments (Reichmuth 2002).

Dwinell (2001a) found that the pine wood nematode did not survive in air-dried pine lumber that had been pressure treatment with chromated copper arsenate. Regulatory actions in some countries have eliminated the use of this substance. *Heat* treatment also has great potential for the production of pest-free lumber used for solid wood packing material (Dwinell 2001b). The thermosensitivity of microorganisms is generally understood and can be effectively applied to use elevated temperatures to decontaminate wood.

Huhu beetle larvae *Prionoplus reticularis* (Coleoptera: Cerambycidae) infestation of sawn, New Zealand pine trees immediately prior to export can result in MB fumigation on arrival in the United States and possibly some Asian countries if pests of quarantine importance are detected. Lester *et al.* (2000) considered gamma irradiation a potential alternative to MB as an irradiation dose of 2.5 – 3.7 kGy killed all larval stages within 3-10 days of treatment.

Eggs and larvae of huhu were also treated at elevated temperatures and varying *controlled atmosphere* conditions (Dentener *et al.* 1999). At 35 ºC in air, more than 9.4 days were needed to achieve 99% mortality of huhu larvae. Eggs and neonate larvae were more susceptible to the heat treatments than were larger larvae. Controlled atmosphere conditions consisting of 100% N_2, 100% CO_2, or a 50% N_2/50% CO_2 mixture at 20ºC achieved less than 36% mortality of large huhu bugs after 11 days exposure. However, increasing the treatment temperature to 40 ºC during 100% N_2, 100% CO_2, and 50% CO_2 N_2/50% CO_2 treatments results in LT_{99} of 8.3, 6.9, and 7.6 h respectively. The 100% CO_2 controlled atmosphere treatment was most effective.

Application of either prophylactic or therapeutic chemicals can control pests on wood packing materials depending on the pests of interest, the wood species and the length of time for which the treatment must be effective (Morrell 2001b). Chemical application can be accomplished using topical surface treatments applied at atmospheric pressure using dipping, spraying, or soaking. The treatment creates a toxic barrier against fungal and insect invasion, kills near-surface insects and fungi that come in contact with the chemical, and prevents organisms already established in the wood from either sporulating on the surface or, for insects, completing their life cycle by exiting the product. Increasing environmental concerns have encouraged the development of narrow spectrum dips, including copper-8-quinolinolate, 3-iodo-2-propynyl butyl carbamate, didecyldimethyl ammonium chloride, propiconazole, tebuconazole, carbendazim, chlorpyrifos, and boron.

There are also a limited number of *chemical solvents*, including copper-8-quinolinolate, copper naphthenate, and pentachlorophenol usually applied in a mineral spirits type of solvent. These solvent-borne treatments are used to a limited extent by the military to treat ammunition boxes, pallets, wire spools and other wood-based materials that must retain their integrity during long-term storage under varying environmental conditions. The high cost of the solvent usually makes these materials less attractive for treating low-value packing materials.

There is interest in irradiation as an alternative to fumigation for the disinfestation of plants, plant products and other materials for pests and pathogens. There is a paucity of information, however, on the use of ionizing irradiation for the control of pests associated chips, logs and sawn wood (Dwinell 2001c). Irradiation to eradicate the pine wood nematode (*Bursaphelenchus xylophilus*) in pine chips has been investigated. Pine wood nematode-infested wood chips were exposed (for periods from 1 h to 2 weeks) to gamma ray doses up to 12 kGy. Lethal doses lay in the range above 6 to 9 kGy, which was considered too high to make irradiation an economically attractive means of decontaminating commercial wood chips. Forintek Canada Corp. researchers reported that a similar dosage of 7 kGy was required to kill pine wood nematodes in aqueous solution, which supports the contention that a higher dosage is necessary to eliminate the pine wood nematode in vivo than in vitro. Recent studies on irradiation effects on nematodes confirmed the relative high dosages required to cause mortality (i.e. a dose of 7.5 kGy was required to kill all J2 larvae of *Meloidogyne javanica*). The use of irradiation for decontaminating chips, logs, or sawn wood does not appear to be economically feasible. Irradiation may, however, be useful in managing pests on high-value forest products that cannot normally be heat-treated or fumigated.

7.9.8 Wood packaging materials

There are some major quarantine issues in durables, the most recent example being disinfestation of wood packing material for control of the Asian longhorn beetle prior to export of manufactured goods from China to the USA, Canada and Australia. MBTOC noted particularly substantial increased use of MB in China for QPS treatment of wood and wooden packing materials as a result of quarantine requirements of USA and Canada. If an alternative to MB is not found, use is likely to increase further with increased trade now that China has become a member of the World Trade Organisation.

7.9.8.1 Existing treatments

An European Union regulation from 1 October 2001 required any non-manufactured, i.e. solid wood packing material (SWPM) and coniferous wooden pallets to be treated to prevent further introductions of the pinewood nematode (*Bursaphelenchus xylophilus)* entering Europe (Anon 2001d). This nematode has caused extensive damage in Japan and China. European concern was heightened due to outbreaks in Portugal due to interceptions of infested pallets shipped from the United States, Canada, China and Japan. Of the 450 million new pallets produced annually in the USA, 30% are pine or made of coniferous wood. EU measures allow disinfestation by *heat, fumigation* or *chemical pressure impregnation*. In order to create a paperless verification system, all treated material and pallets are required to indicate the organisation that treated the wood packing material and the location of the organisation. MB is the fumigant recommended by APHIS, but any fumigant labelled for wood fumigation may be used, e.g. phosphine or sulphuryl fluoride (Anon 2002f).

Under current quarantine procedures, treatment rates for *sulphuryl fluoride* are provided for fumigation of non-food cargo against wood-infesting beetles (Anon 2002f). Infested wooden packages for export to China from Japan are treated by vapour heat (56ºC for 30 minutes) (F. Kawakami, pers.comm. 2001).

7.9.8.2 Potential treatments

The IPPC Standard ISPM No. 15 could be approved as a viable alternative for countries that have the necessary infrastructure to carry out and document the treatment (Anon 2002). The Standard states that there are thirteen alternative treatments (phosphine, sulphuryl fluoride, carbonyl sulphide, four chemical pressure impregnation techniques, five types of irradiation, and controlled atmospheres) that are being reviewed and once their efficacy is accepted they will be included in future revisions of the Standard. These treatments could be considered as alternative treatments to MB.

7.9.9 Tobacco and cotton

7.9.9.1 Existing alternatives

Tobacco is a high value commodity that is transported internationally either raw or as finished products (cigars, cigarettes and pipe tobacco). Countries that export to Japan can choose either phosphine or MB as quarantine treatment for tobacco. HCN is still used to treat cotton against quarantine cotton pests on import into India, a process developed many years ago (Turner and Sen 1928).

7.9.9.2 Potential alternatives

MBTOC is not aware of any current research on alternative treatments to MB to control pests on post harvest cotton. However, in the past heat have been used successfully against pink bollworm using 55-58ºC for 5 minutes (Storey 1921, El Gammal, 1940).

7.9.10 Miscellaneous

7.9.10.1 Existing alternatives

Phosphine is an approved treatment to control potential infestations of Hessian fly, *Mayetiola destructor*, in compressed hay for export from the USA and Australia to Japan (Anon 2002f), based on a treatment schedule developed by Yokoyama *et al.* (1999). Wrapping bales in low density polyethylene bales did not affect the efficacy of the treatment.

Phosphine is used in Europe to fumigate wooden objects, paper and other materials of organic origin. With some materials, e.g. furs and paper, phosphine may be preferred to MB because of the reduced risk of taint (Reichmuth 2002). Phosphine may adversely affect metals like copper, silver and gold and pigments in paintings and is therefore rarely used for treating objects of this type. Fumigation with this gas requires a longer exposure period than MB for complete control of insects.

7.9.10.2 Potential alternatives

Carbonyl sulphide at 60 g m^{-3} for 48h at 25-35°C applied to hay in a shipping container was estimated to cause more than 99% mortality of *Sitophilus oryzae* mixed-age cultures used as bio-indicators (Weller and van S. Graver 2002). With further refinement of the technique, this treatment showed promise as a quarantine treatment to replace phosphine (7 day) or carbon dioxide (14 day) treatments approved by MAFF-Japan for shipments from Australia.

McGuire (2000) showed that the marketability of harvested leaves of the curry leaf tree (*Murraya koenigii*) was unlikely to be affected by cool storage treatment of 15 days at 1ºC, or up to 1 kGy of gamma irradiation. Tests have yet to be undertaken on the Asian citrus psyllid, *Diaphorina citri*, previously intercepted on leaves imported into the USA. The psyllid also implicated in the transmission of a bacterium that is considered to cause citrus greening disease that severely affects citrus trees.

7.10 Summary of Existing and Potential Alternatives to Methyl Bromide for Quarantine and Pre-shipment

MBTOC recorded more than 300 alternative quarantine treatments for perishable commodities and more than 70 QPS treatments for durables approved by a Regulatory Agency, largely compiled from the United States Department of Agriculture - Animal and Plant Health Inspection Service Treatment Manual. However, although this number is approved, actual use of these treatments is not well documented. Despite this number and range of quarantine treatments, only a small proportion of commodities in commercial trade are treated in the export country using these alternatives.

The range of alternative treatments identified by MBTOC for perishable commodities is summarised in Tables 7.4, 7.5, 7.6 and 7.7 taken largely from the USDA-APHIS Treatment Manual, the Japanese Treatment Manual and the existing QPS treatments reported in this chapter.

Table 7.4 Approved quarantine treatments for fresh fruit, vegetables and cut flowers

Procedure or treatment	Examples of approved quarantine applications
Cold treatments	Many approved cases – see Table 7.2 for examples.
Heat treatments	Bell pepper to the USA (vapour heat) Citrus from Hawaii to the USA (heated air) Egg plant to the USA (vapour heat) Grapefruit from Mexico (heated air) Mango from Taiwan to USA (vapour heat) Mangoes from Australia, China, Hawaii, Philippines, Taiwan and Thailand to Japan Mango from Mexico, Central and South America and the Caribbean to the USA (heated air or vapour heat) Mango, papaya, sweet pepper, netted melon, bitter cucumber and sweet potato from southern islands of Japan to mainland Japan Mango to the USA (hot water dip) Mountain papaya from Chile to USA (heated air) Mountain papaya to USA (vapour heat) Papaya and litchi from Australia, China, Hawaii, Philippines, Taiwan and Thailand to Japan Papaya from Fiji, Tonga, Cook Islands and New Caledonia to New Zealand Narcissus bulbs to Japan Orange, grapefruit and tangerine from Mexico to USA (vapour heat) Papaya to USA (vapour heat) Papaya from Belize and Hawaii to USA (heated air) Papaya from Hawaii, Philippines and Okinawa Island to Japan Pineapple to USA, other than smooth cayenne (vapour heat) Squash to USA (vapour heat) Tomato to USA (vapour heat) Zucchini to USA Babaco for export to the USA from two areas of Chile (vapour heat)
Certified pest-free zones or pest-free periods	Cucurbits to Japan and USA Grapes, kiwifruit and other produce from southern Chile to Japan Immature banana to Japan Melons from a region of China to Japan Peach, nectarine from USA to Brazil, Ecuador, Colombia and New Zealand Squash, tomatoes, capsicum, eggplant from Tasmania (Australia) to Japan Strawberry, cucumber, bell pepper, tomato, eggplant, grapes, squash and melon from the Netherlands to Japan
Systems Approach	Apples from USA to Brazil Apples from Australia and New Zealand to Taiwan Avocado from Mexico to 19 northeastern States in the USA Citrus from Florida to Japan
Pre-shipment inspection and certification	Apples from Chile and New Zealand to USA Certain cut flowers from Netherlands and Colombia to Japan Garlic from Italy and Spain to USA Green vegetables to many countries Nectarines and apricots from New Zealand to Australia
Inspection on arrival	Small batches of seeds for propagation to USA
Physical removal of pests	Hand removal of certain pests from cut flowers to USA Propagative plant materials (unable to tolerate MB fumigation) to USA Root crops are accepted by many countries if all soil removed
Controlled atmospheres	Apples from Canada to California, with cool storage
Pesticides, fumigants and aerosols	Asparagus and other vegetables to Japan infested with thrips and aphids (HCN) Bulbs to Japan Certain ornamental plants to USA Cut flowers from Hawaii and New Zealand to Japan Cut flowers from Hawaii to mainland USA Cut flowers from Thailand to Japan Propagative plant material to USA

Procedure or treatment	Examples of approved quarantine applications
Irradiation	USDA-APHIS published a proposed rule to establish phytosanitary requirements that once finalised allows the use of irradiation treatments for imported fruits and vegetables. The proposed rule established irradiation doses for 11 fruit flies and one seed weevil and is based on the pest requirements rather than on the commodity. Garlic Papaya from Hawaii Papaya, carambola and litchi from Hawaii to USA Plums from South Africa to France
Combination treatments	Hand removal + pesticide for certain ornamental plants, Christmas trees and propagative plant materials to USA Heat treatment + removal of pulp from seeds for propagation to USA Ornamentals from Hawaii to USA (hand removal + high pressure water + malathion / carbaryl dip if necessary) Soapy water and wax coating for cherimoya and limes from Chile to USA Vapour heat and cold treatment for litchi from China and Taiwan to Japan Warm soapy water + brushing for durian and other large fruit to USA Tomatoes from Australia to New Zealand Apricots based on pest free zone + cold storage for export to the USA from two areas of Chile

Sources: Compiled mainly from this chapter and USDA-APHIS (Anon 2002f) and Japan Treatment Manual (1982)

Table 7.5 Approved quarantine treatments for fresh fruit using cold conditions (USDA-APIS PPQ Treatment Manual 2002)

Perishable commodity	Examples of cold treatments approved for quarantine
Apple	• From Mexico, Chile, South Africa, Israel, Argentina, Brazil, Italy, France, Spain, Portugal, Jordan, Lebanon, Australia, Hungary, Uruguay, Ecuador, Guyana and Zimbabwe to USA
Apricot	• From Mexico, Israel, Morocco, Zimbabwe, Haiti and Argentina to USA
Avocado	• From Hawaii (cv Sharwill) to mainland USA • From Western Australia to eastern Australian states
Carambola	• From Hawaii, Belize and Taiwan to USA • From USA to Japan • From Florida to California
Cherry	• From Mexico, Chile and Argentina to USA
Citrus	• From Florida (USA), Chile, Australia, China, Hawaii, Israel, Philippines, South Africa, Spain, Swaziland and Taiwan to Japan • From South Africa (Western Cape) to USA • Interstate USA
Clemantines	• From Israel, Spain, Morocco, Costa Rica, Colombia, Guatemala, Honduras, Ecuador, El Salvador, Nicaragua, Panama, Venezuela, Suriname, Trinidad and Tobago, Algeria, Tunisia, Greece, Cyprus and Italy to USA • Interstate USA
Durian	• To USA
Ethrog	• From Israel, Costa Rica, Ecuador, El Salvador, Guatemala, Honduras, Nicaragua, Panama, Morocco, Spain, Italy, France, Greece, Portugal, Tunisia, Syria, Turkey, Albania, Algeria, Belize, Bosnia and Herzegovina, Macedonia, Croatia, Libya, Corsica and Cyprus to USA
Grape	• From Australia, Hawaii, Israel, Philippines, South Africa, Spain, Swaziland, Taiwan, Chile, the Netherlands to Japan • From South Africa, Brazil, Colombia, Dominican Republic, Ecuador, Peru, Uruguay, Venezuela and India to USA
Grapefruit	• From Israel, Mexico, Costa Rica, Guatemala, Honduras, El Salvador, Nicaragua, Panama, Colombia, Bolivia, Venezuela, Italy, Spain, Tunisia, Australia, Suriname, Trinidad and Tobago, Belize, Bermuda, Cyprus, Algeria and Morocco to USA • Interstate USA

Perishable commodity	Examples of cold treatments approved for quarantine
Kiwifruit	• From Chile, Australia, China, Hawaii, Israel, Philippines, South Africa, Spain, Swaziland and Taiwan to Japan • From Chile, Italy, France, Greece, Zimbabwe and Australia to USA
Litchi	• From China, Israel and Taiwan to USA
Loquat	• From Chile, Israel and Spain to USA
Nectarine	• From Israel, Argentina, Uruguay, Zimbabwe and South Africa to USA
Orange	• From Israel, Mexico, Spain, Morocco, Costa Rica, Colombia, Bolivia, Honduras, El Salvador, Nicaragua, Panama, Guatemala, Venezuela, Guyana, Belize, Trinidad and Tobago, Suriname, Bermuda, Italy, Greece, Turkey, Egypt, Algeria, Tunisia and Australia to USA • Interstate USA
Papaya (mountain)	• From Chile to USA
Peach	• From Mexico, Israel, Morocco, South Africa, Tunisia, Zimbabwe, Uruguay and Argentina to USA
Pear	• From Israel, Chile, South Africa, Morocco, Italy, France, Spain, Portugal, Egypt, Tunisia, Algeria, Uruguay, Argentina, Zimbabwe and Australia to USA
Persimmon	• From Israel, Italy and Jordan to USA
Plum	• From Mexico, Israel, Morocco, Colombia, Argentina, Uruguay, Guatemala, Algeria, Tunisia, Zimbabwe and South Africa to USA
Plumcot	• From Chile to USA
Pomegranate	• From Israel, Colombia, Argentina, Haiti and Greece to USA
Pommelo	• From Israel to USA
Quince	• From Chile and Argentina to USA
Tangerine	• From Mexico, Australia and Belize to USA • Interstate USA
Ya pear	• From China to USA

Sources: Compiled from this chapter and USDA-APHIS (Anon2002f).

Table 7.6 Approved quarantine and pre-shipment treatments for durable commodities

Procedure or treatment	Examples of approved quarantine and pre-shipment applications
Bifluorides	Timber exported to the European Community
Carboxide	Non-plant articles infested with ticks, to the USA
Cold	Museum artefacts for export or temporary loan (freeze treatment) Museum artefacts that will tolerate cold, imported by Europe Items infested with insects in soil, into the USA (freeze treatment) Pecans and hickory nuts to the USA
Combination Treatment	Contact insecticides and water immersion for logs imported by Japan
Controlled atmospheres	Containerised cargo in transit (CO_2) Rodents in aircraft (CO_2) Dried figs from Turkey Bulk grain from Cypress (hermetic storage) Quarantine pests of grain to Japan (CO_2) Museum artefacts for export or temporary loan (N_2) Tobacco products, cocoa beans, rice, cereals, grains, nuts, peanuts, pulses, seeds and spices as well as furniture and artefacts, in Europe Dried fruit and beverage crops in Europe (CO_2 plus high pressure) Packaged dried fruit, cereals and nuts (gas flushed or vacuum packed)
Debarking	Logs
Ethyl formate	Prepacked dried fruit in Australia and South Africa

Procedure or treatment	Examples of approved quarantine and pre-shipment applications
Heat	Timber and timber packing from China to USA Any durable commodity that can tolerate heat (khapra beetle) to the USA Feeds and milled products for processing, into USA Bagasse and sugar cane to USA Bags for seeds Lumber (3" thick) with wood borers to USA Corn (maize) ears, not for propagation, to USA Rice straw novelties and articles to USA Niger seeds (contaminated with soil or khapra beetle) to USA Seeds not for propagation (steam), to USA Rice straw and hulls, straw mats and rice straw novelties to USA (steam pressure) Novelties and articles from broom corn, to USA (steam pressure) Leaf tobacco and blended-strip tobacco for export from USA (steam vacuum) Bulbs infested with *Ditylenchus* nematodes, into USA (hot water dip) Lily bulbs and with Aphelenchoides nematodes into the USA (hot water dip) Narcissus bulbs with bulb scale mite into the USA (hot water dip) Certain tubers wit *Meloidogyne* spp to the USA (hot water dip) Horse radish root with golden nematode to USA (hot water dip) Banana roots to USA (hot water dip) Sugar cane to USA (hot water dip) Sawn timber for export (kiln drying) Storage bins and other grain handling equipment moved interstate USA for control of Karnal bunt (steam heat) Museum artefacts that tolerate heat, in Europe Packaging material from China to Japan (vapour heat) Khapra beetle in bulk grain
Hydrogen cyanide	Rodents and insects in ships and aircraft in Singapore and France Cotton to India Bulbs to Japan (bulb fly and thrips)
Irradiation	Wooden artefacts imported by Australia
MITC	MITC on logs to Japan
Phosphine	Timber to the USA Bamboo treated in transit to Japan Tobacco for export from the USA Logs (longhorn and bark beetles, wood wasps and platypodids) registered only in the USA Cotton, cotton waste and cotton products in bulk imported into the USA Seeds of cotton, packaged or bulk, to USA Seeds and dried pods, kenaf and others imported by the USA Wooden items infested with wood borers imported by the USA Seafreight containers in transit on ships Compressed hay to Japan and the USA Wooden objects and other materials of organic origin to Europe Cocoa and other durables to Germany Bulk and bagged and other durable commodities to many countries Packing materials to the USA
Sulphuryl fluoride	Pre-shipment fumigation of seafreight containers sent to Europe Packing materials to the USA Non-plant articles infested with ticks, to the USA Wooden items infested with wood borers, to USA Wood products and containers with termites, to USA

Source: Compiled from text in this chapter; and USDA-APHIS-PPQ Treatment Manual

Table 7.7 Number of known cases where countries have approved an alternative QPS technique for perishable or durable commodities (or groups of similar commodities)

Alternative procedure or technique	Identified cases where a country has approved an alternative quarantine treatment for perishable commodities	Identified cases where a country has approved an alternative QPS treatment for durable commodities
Bifluorides	-	1
Carboxide	-	1
Cold	> 240[1]	1
Combination treatment	8	1
Controlled atmospheres	1	23
Debarking	-	1
Ethyl formate	-	1
Heat	24	33
Hydrogen cyanide	-	3
Inspection on arrival	1	-
Irradiation	Many possible	1
MITC	-	1
Modified atmospheres	0	0
Pest-free zones or periods	7	-
Pesticides, aerosols, fumigants	7	-
Phosphine	-	Many
Physical removal of pests	3	-
Pre-shipment inspection	5	5
Systems Approach	4	-
Total identified to date	>> 303	>> 70

[1]9 schedules for 55 countries

7.11 Research Priorities for Alternatives to Methyl Bromide for Quarantine and Pre-shipment

Despite the limitations on the development of alternatives for QPS discussed in Section 7.6, there are several reasons for continued and strong interest in the development of alternatives to MB for QPS:

1. The Parties to the Montreal Protocol may decide to limit the use of MB for QPS for Parties not operating under Article 5(1), rather than allow the current exemption to continue, in line with national action already taken by some developed countries. Uncertainty in the future exemption for the use of MB for QPS is therefore a reason for some Parties to pursue research leading to the development of alternatives for this use.

2. Some countries – both Article 5(1) and non-Article 5(1) - propose to ban non-QPS use of MB earlier than the phase out date scheduled under the Protocol. Based on current trends of increasing MB cost with decreased global requirements, some Parties wish to pursue research in order to find alternatives that could be more cost-effective than MB;

3. All plant regulatory authorities are charged with protecting agriculture in their own country by excluding regulated quarantine and non-quarantine pests. If MB becomes difficult to obtain and/or is very costly, and in the absence of an alternative, smuggling of commodities could increase which, as the commodities are not being checked when entering the country or state, increases the risk of quarantine pests entering commercial agricultural production;

4. In the absence of a viable alternative and if MB is not available, plant regulatory authorities that have intercepted a consignment with regulated quarantine or non-quarantine pests would need to destroy or return the consignment. This action would result in a restricted range of products being available at retail level to the public. The food retail chains and the public would regard the plant regulatory authority as responsible for the lack of availability of particular products;

5. MB treatment can sometimes be damaging to one variety e.g., Ohrin apples and not to another variety e.g. Gala apples, when used under identical treatment conditions and equivalent apple maturity. There is therefore interest in developing treatments that are less detrimental on the quality and/or shelf-life of some commodities and some varieties; and

6. Most developed countries that are reliant on income from the export of perishable and durable commodities are investing in research on chemical and non-chemical alternatives to MB to avoid long-term dependency on MB. The research priorities for alternatives to MB are different for Article 5(1) and non-Article 5(1) countries because each has different market requirements and economic constraints.

7.11.1 Article 5(1) (developing) countries

Postharvest treatments using MB are more common for perishable commodities exported from Asian and Latin American countries than Africa that, apart from South Africa and Zimbabwe, have relatively few exports. MB is mainly used to disinfest cut flowers, vegetables and fruit in Asia and Latin America. Despite this varying usage, developing countries have similar requirements that include:

- Obtaining the appropriate disinfestation technology;
- Transferring this technology to the local environment;

- Training personnel to carry out new disinfestation treatments;
- Obtaining sufficient funds to allow completion of the research to demonstrate efficacy;
- Training in the commercial use of alternatives.

Ideally, any alternative treatment to MB must be appropriate to the local conditions, i.e., cost-effective, safe to apply, environmentally sound, simple to use and require minimal maintenance. Promising technologies must be tested in the Article 5(1) countries. Highly skilled personnel are required to adapt the technology to the local conditions, train local staff in its effective use and develop treatment and operational manuals in collaboration with technical staff.

Article 5(1) countries largely depend on developed countries to develop and test alternative treatments to MB for QPS purposes, and to assist in the costs of transferring the technology for implementation. For example, a heat treatment for papaya was developed in the United States (Armstrong *et al.* 1989) and then modified by New Zealand for use in the South Pacific (Waddell *et al.* 1993). This process is now used on Cook Island papaya exports, replacing the banned ethylene dibromide. The project was financed by a consortium of government and private organisations.

The choice of alternative will be determined largely by the commodity tolerance, the target pest, the potential for success based on previous research and capital and operational costs. Deang (2002) recently reviewed the use of non-MB QPS treatments in developing countries. Most research in Article 5(1) countries currently is based on heat disinfestation as most are located in tropical or subtropical regions of the world. There is also some research on irradiation for high value fruit exports because most tropical commodities have been shown to tolerate these treatments.

Key personnel should attend conferences, workshops and training courses. Information on post-harvest alternatives must be written in the appropriate technical language and published in scientific journals and bulletins.

Article 5(1) countries require clear guidelines for the development of disinfestation treatments. A technical expert from a developed country may be necessary to assist with experimental design (including equipment, lifestages, commodity quality) and report documentation necessary for demonstrating quarantine security. Ongoing exchange visits to developing countries by scientists and technicians are essential for effective collaboration in projects that test and implement alternatives.

To ensure continuity of skilled personnel, quarantine officers and students should be encouraged to undertake courses essential to the development and implementation of alternatives, particularly those related to plant physiology, entomology, engineering and related areas. International companies with facilities in developing countries should be encouraged to increase their technology transfer expenditures.

The horticultural industry is concerned that alternatives are not available to substitute for MB for all of its post-harvest uses (Kidd 1999) but recognises that some alternatives such as heat and/or cold treatments, irradiation and the Systems Approach are available. However, they are also concerned that these treatments are more complex than MB and might often has higher costs compared to current MB prices. These factors will also impede adoption of QPS alternatives in developing countries.

MBTOC notes the necessity to ensure technology transfer to help reduce the disparity in postharvest treatment costs for exports from both non-Article 5(1) and Article 5(1) countries.

The following are not known to have alternatives to MB for QPS treatments in developing countries:

- Grapes exported from Chile to the USA; and
- Cut flowers (roses, carnations and statice) exported from developing countries to Europe, USA, Scandinavia and Japan.

7.11.2 Developed countries

Most research involves the development of heat, cold, CA, MA and combinations of these alternatives in the short term because these have shown the most potential for many commodities. Treatments based on pre-harvest procedures (inspection, pest-free zones and periods and the systems approach) are also high priority, but are longer term since considerable documentation on pest security is required by regulatory agencies. Irradiation research is usually given medium priority as scientific information on the effects on the commodity and the pest is generally recognised as sufficient, although high priority is given if other alternatives are less promising. Some researchers have reported that, compared to MB, alternatives involving CO_2, PH_3 and SF or mixtures of these gases have the disadvantages of relatively long exposure times, narrow pest range, a requirement for very air-tight facilities and often higher operating costs.

The following are not known to have alternatives to MB for QPS treatments in non-Article 5(1) countries and therefore could be considered as high priority for research:

- ***Apple*** exports potentially infested with codling moth to countries free of codling moth. This is important for New Zealand and the United States exports to Japan.
- ***Stonefruit*** (peaches, plums, cherries, apricots, nectarines) exports potentially infested with codling moth in Japan and other countries where this pest is listed as quarantine pest of major importance.
- ***Grapes*** from Chile potentially infested with *Brevipalpus chilensis* mite on exports to the United States; and grape exports from the USA to countries that currently require MB fumigation.
- ***Berryfruit*** (internal pests in strawberry, raspberry, blueberry and blackberry). Exports are economically important for countries such as the United States, New Zealand, Colombia, Australia, Israel, Brazil, South Africa, Canada and Zimbabwe.
- Some ***root crops and bulbs*** (carrot, cassava, garlic, ginger, onion, taro and yam) that are susceptible to heat disinfestation. Some of these crops are exported in minor volumes (but often economically significant) from developing countries to ethnic groups in developed countries.
- ***Oak logs*** exported to Europe from the United States potentially contaminated with oak wilt fungus;

- Codling moth and a variety of other stored product pests potentially infesting ***walnuts*** for export without any pre-shipment storage; and

- Seed-borne nematodes from alfalfa and some other ***seeds for planting.***

7.12 Opportunities to Reduce Methyl Bromide Emissions from Quarantine and Pre-shipment Uses

Most MB fumigations of perishable and durable commodities are carried out in fixed structures such as fumigation facilities, shipping containers or silos. Logs and bag stacks are treated under tarpaulins. For perishable commodities, about 90% of the MB is released to the atmosphere from these fumigations as, in contrast to durable commodities such as wheat and rice, perishable commodities absorb less than 15% of the MB used in a fumigation treatment. Equipment is now available to recapture MB from QPS treatments carried out in well sealed enclosures, as normally recommended (see Chapter 8).

The first priority must be to replace MB with an alternative treatment. However, if this is not possible, an interim strategy must be to reduce the amount of MB released to the atmosphere. This could be achieved by either MB dosage reduction or by fitting fumigation facilities with MB recapture equipment.

Dosage reduction can be relatively inexpensive compared to the costs of adding recapture equipment to the facility. Key ways to reduce dosages for QPS fumigation of perishable and durable commodities are to:

1. Increase either the temperature or the time, or both. High temperature schedules with or without longer fumigation durations are more likely to be feasible for durable commodities as often the marketability of perishable products is reduced under such conditions;

2. Add forced air circulation, as the fumigant will be circulated more efficiently in the facility. Carbon absorbers (Kawakami and Soma 1991) can also absorb the MB after the treatment which reduces the both reduces emissions and helps to reduce any phytotoxicity;

3. Improve the gastightness of fumigation facilities to prevent unwarranted leakage of MB into the atmosphere. Simple test criteria have been provided to the industry for determining the gas tightness of chambers (Bond 1984);

4. Measure accurately the dosage using sensitive weighing scales or a measuring cylinder with dispenser; and

5. Use a combination of gases e.g. MB with carbon dioxide and phosphine, to achieve a reduction in MB. Combination treatments are less phytotoxic to cut flowers and ornamentals than MB or phosphine alone and have the same insecticidal activity (Kawakami *et al.* 1996).

If further dosage reduction is not possible, commercial equipment to recapture MB could be considered for attachment to the fumigation chamber. Some facilities have the potential to allow about 80% of the recovered gas to be used in the next fumigation, depending on commodity adsorption and losses to the facility. Further detail is provided in Chapter 8: and in the 2002 Report of the Task Force on Collection, Recovery and Storage (TEAP 2002a).

Some recapture equipment does not allow the gas to be re-used. Instead, it is transported to a destruction facility. Since destruction facilities are usually not present in developing countries, the use of such technology is largely confined to non-Article 5(1) countries. The use of recapture equipment will depend mainly upon the level of emission reduction required, on the cost-benefit of MB recovery and recycling, and, if the MB is to be reused, on regulatory approval for recycling chemicals for use on food that may contain contaminants.

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Chapter

8

Reducing methyl bromide emissions

8.1 Introduction

During any fumigation operation there are three distinct sources or opportunities for MB to be emitted to the atmosphere:

i. By leakage during the actual fumigation treatment.

ii. During venting of the fumigation space immediately after fumigation or removal of the cover sheets where a deliberate discharge to the atmosphere takes place.

iii. Following treatment when the treated soil, commodity or structure slowly emits any adsorbed MB.

The first and to some extent the third situation can be controlled or reduced by better containment of the fumigation site (Section 8.3 (soil treatments) and 8.6 (commodities)). Leakage in these instances is undesirable from the fumigation perspective as it reduces the effectiveness of the treatment as well as having worker safety implications. The second situation can only be controlled by recapture of the MB (recovery) followed by recycling, reclamation or by destruction (Sections 8.8 and 8.9). For most fumigation operations, venting following fumigation results in the largest potential discharge to the atmosphere.

Section 8.2 estimates the global amount of MB emitted from current uses; Section 8.10 considers opportunities for reducing MB application rates and finally Section 8.11 discusses constraints to their implementation.

8.2 MB Emissions from Current Uses

A proportion of any applied dosage of MB reacts with the treated material such as soil, grain, fruit or the associated structures and packing material. The end product of this reaction is typically the non-volatile bromide ion, various methylated products and carbon dioxide. These have not been identified as ozone depleters. The proportion of non-volatile bromide residue formed as a result of a treatment is a direct measure of the proportion of the applied MB *not* emitted to atmosphere. The proportion emitted is found by difference. This 'mass balance' approach is typically used to estimate quantities of MB released to atmosphere from a treatment. It gives a conservative estimate and is simple to use as bromide ion tends to be easily detected and quantified. An allowance must be made for natural bromide ion already present prior to treatment.

An alternative approach is to observe the quantities emitted directly. This is experimentally difficult as it relies on quantification of a number of fluxes of gas and may miss some important ones. The approach tends to underestimate the emissions, but is often used in soil fumigation studies.

The proportion of applied MB converted to fixed residues and thus not released to the atmosphere, varies widely with the particular treatment situation. It is influenced, *inter alia*, by the degree of gastightness (sealing, permeability of the enclosure) and the temperature, moisture content and reactivity of the treated material (e.g. soil, commodity). With soil fumigation, the mode of application is also a major factor since it influences the contact time between the MB and substrate and thus the opportunity for varying degrees of reaction and dispersion within the soil before loss from the system.

There is remarkably little firm quantitative field data available on the production of bromide ion or other measures of loss of MB from particular systems. For the purposes of this report, as in previous Assessments, MBTOC has relied on some particular data for specific situations and estimates provided by MBTOC members. Ranges of estimates have been given. These are used to encompass both the true variability to be expected with different sites, techniques and situations and also the range of opinions expressed by experts within MBTOC. An approximation of the quantity of MB lost to the atmosphere has been made by integrating this information over the total usage of MB (Table 8.1) Supporting calculations for some of the emission levels used in these calculations are given in MBTOC (1998).

Table 8.1 includes estimates for emissions from five types of application to soils. The variation given in two of these is wide and reflects the range of data available to MBTOC experts. It is not possible to provide a weighting of figures within these ranges to give a precise average emission as the distribution of emissions over the global range of practice cannot be estimated because of lack of data. However, it may well be that the true value differs substantially from the average value of range quoted.

The overall usage figures given in Table 8.1 are derived from estimates of 2000 production (Section 3.4). The usage figures for the individual sectors are based on tonnages used in various applications derived from previous estimates from the various MBTOC sub-committees. Under current usage patterns, the proportions of applied MB eventually emitted to the atmosphere are estimated by MBTOC to be 40 - 87%, 85 - 98%, 69 - 79% and 90 - 98% of applied dosage for soil, perishable commodities, durable commodities and structural treatments respectively. These figures, weighted for proportion of use and particular treatments, correspond to a range of 50 - 87% overall emission from agricultural and related uses, with a best estimate of overall emissions of 73%, or 40,515 metric tonnes based on production of 56,599 tonnes in 2000.

Table 8.1 Estimated global usage of MB and emissions to atmosphere for different categories of fumigation by major use category.

Type of fumigation and commodity/use	Estimated usage		Estimated emissions	
	tonnes	%	tonnes	% (a)
Enclosed space - durables				
Grains, nuts, dried fruit etc.	4,302	7.6	2,194 – 3,011	51 - 70
Timber, pallets, packaging…	4,188	7.4	3,686	88
Subtotal - durables	*8,490*	*15.0*	*5,880 – 6,697*	*69 – 79*
Enclosed space – structures	1,415	2.5	1,273 – 1,387	90 – 98
Enclosed space – perishables	4,811	8.5	4,089 – 4,715	85 – 98
Soil fumigation				
Soil injection – shallow with PE tarp	22,640	40.0	6,399 –20,149	28 – 89
Soil injection – deep with tarp	1,698	3.0	357 – 509	21 – 30
Soil injection – deep without tarp	849	1.5	679	80
Vapourised gas – with PE tarp	7,075	12.5	2,830 – 6,509	40 – 92
Small cans – with PE tarp	7,924	14.0	6,339 – 7,290	80 – 92
Soil treatment, with VIF	1,698	3.0	340 – 1,189	20 – 70
Subtotal - soil fumigation	*41,883*	*74.0*	*16,883 – 36,325*	*40 – 87*
Total reported fumigant	**56,599**	**100.0**	**28,126 – 49,123**	**50 – 87**
Best estimate over all categories			41,317	73 (b)

a for sources of estimates, see MBTOC (1995,1998
b MBTOC recognises that the true value of emissions may differ substantially from this best estimate.

Calculations based on 2000 reported production data, excluding feedstock (Ozone Secretariat data). Total fumigant tonnage is based on incomplete data reports, so actual tonnage may be slightly higher than indicated.

8.3 Emission Reduction through Better Containment

Improving the gastightness of a fumigation treatment can provide three potential pathways for reducing the emission of MB. These are:

i) by limiting the release to the atmosphere of any MB leaking during the treatment,

ii) by allowing lower initial MB dosages or MB top-ups to be applied, and

iii) by prolonging the effective fumigation period allowing increased opportunity for breakdown of MB on the commodity, structure or substrate.

8.3.1 Soil fumigation

It is generally understood, that MB emissions to the atmosphere from soil fumigation can come from any of three major sources:

i) MB emitted through plastic sheets during fumigation;

ii) MB lost from edges during fumigation; and

iii) MB emerging from soil after lifting the sheets after fumigation.

Table 8.2 Estimated emission loss to the atmosphere from soil fumigation

Type of fumigation	% MB emitted	Source
Soil injection, shallow (25 cm) with tarp	34 – 87	Yagi *et al.* (1993,1995)
	32 – 89	Majewski *et al.* (1995)
	61 (average)	Yates *et al.* (1996)
	45	Williams *et al.* (1997)
Soil injection, deep (60 cm) with tarp	21 – 30	Yates *et al.* (1997) MBTOC estimates
Soil injection, deep (60 cm) without tarp	80	MBTOC estimates
Hot gas with tarp	40 – 92	MBTOC estimates

The total emitted is unlikely to be 100% of that applied because of breakdown of applied MB in the soil. Degradation is due to reaction with soil organic matter and some mineral constituents as well as other reaction pathways such as hydrolysis (De Heer *et al.* 1983). It is estimated that emission ranges from is 40-92% from the standard polyethylene (PE) sheeting still predominantly used worldwide for soil fumigation from hot gas treatments (Table 8.2). Emissions from soil injection at 25 cm (‘shallow injection’) are generally around 15% less.

8.3.2 Use of plastic covers

In many countries, regulations require plastic sheets for 3 to 5 days to retain as much MB as possible in the soil. Although many types of film can be used for fumigation (Bakker 1993, de Heer *et al.* 1983, Hamaker *et al.* 1983) thin (approx. 30 μm to 40 μ m) high or low density polyethylene tarps (HDPE or LDPE) are generally applied.

There is a trend towards use of HDPE or VIF in developed countries to improve containment of the gas.

The barrier properties of films can vary considerably based on plastic composition, windspeed, temperature and film thickness (Basile *et al.* 1986, de Heer *et al.* 1983). For example, high density polyethylene films tend to provide a greater barrier to MB than low density polyethylene films. Also for monolayer films, there is a direct correlation between film thickness and permeability to MB, as film thickness increases, permeability decreases. The development of virtually impermeable films (VIFs), which are significantly less permeable to MB than LDPE (van Wambeke *et al.* 1983, Thomas 1998), offers an opportunity for significant reduction in emissions. Although the European Union now requires mandatory use of VIF films for covers during soil fumigation (EU regulation 2037/2000), their commercial use world-wide is still limited due to availability, cost and difficulties with handling in the field (Bakker 1993, Thomas 1998).

8.3.3 Virtually impermeable films

VIF film consists of either 1) multi-layer laminates with outer layers of low density polyethylene and a barrier layer of polyamide or ethylene vinyl alcohol, or 2) a mixture of these materials, often call an "alloy".

Field research has shown that the use of VIF agricultural films can reduce emissions to less than 4% of applied MB under some well controlled and specialised conditions, compared with emissions of 68% of applied MB when using HDPE under similar conditions (Yates *et al.* 1998).

In general, VIF can reduce MB emissions from soil fumigation by keeping the MB in the soil to allow for degradation (Yates *et al.* 1998) when:

- The entire field is covered with VIF film;
- All film strip over-laps are well glued and sealed;
- The VIF film edges are sealed (buried under soil);
- The MB is injected deeply in the soil;
- The film is kept on the field, completely sealed, for 10 to 20 days; and
- The soil temperature, moisture and organic matter content are optimal - medium temperatures, moist soil, low organic matter.

VIF is inefficient, if not entirely ineffectual, at reducing MB emissions from soil fumigation (Rice *et al.* 1996, Thomas 1998, Wang *et al.* 1999) when:

- Only part of the field is covered with VIF;
- Any of the film strip over-laps become unglued or are otherwise unsealed;
- Any of the film edges anywhere around the field become unsealed;
- The film seal is broken before 10 to 20 days have passed; and

- Soil temperature, moisture, organic matter are in any way sub-optimal (hot, soil dry or very wet with little organic matter).

Application of VIF and handling characteristics of VIF tend to be less favourable than HDPE films (Gamliel *et al.*1998, Thomas 1998, Wang *et al*. 1998a). VIF film leakage at the edges and overlaps, cracks from photo-deterioration of VIF and holes from animals crossing the field before the MB is degraded will result in MB emissions, especially if the leakage is near the beginning of the fumigation. The longer the VIF film is on the soil, the more likely both the film and seal points could deteriorate due to wind or other weather conditions. Because of the greater MB retention by VIF compared to PE film, there is greater risk of farm worker and residential exposure unless conditions under the film promote MB degradation (Thomas 1998).

Because logistical realities may make it difficult to keep the VIF tarp on the soil for sufficient time to allow for degradation, several researchers are investigating ways to reduce the time necessary for degradation. Research has been conducted on:

1) the response of fumigant emissions to the addition of nitrogen fertilisers and organic amendments (Gan *et al*. 1998);

2) augmenting specific MB degrading soil bacteria to increase the degradation rate (Miller *et al.* 1999, Ou 1998); and

3) the addition of materials such as titanium dioxide to the agricultural film itself (Kobara *et al*. 1999).

While these methods and products have succeeded in enhancing degradation of MB in the laboratory and small-scale tests, full-scale field tests will be necessary in the near future to ensure commercial viability.

Work is on-going to address the problems associated with the use of VIF film to reduce MB emissions. Some researchers are optimistic that the current obstacles can be overcome (Watanabe *et al*. 1999, Rimini 1999, Yates *et al*. 1998). Near-term, focused research will be needed to ensure that this technology is available in a practical form for commercial agriculture for use both with MB and alternatives (such as metham sodium, 1,3-D, chloropicrin). Many gaseous alternatives to MB also are lost by permeation through PE films and their retention and efficacy is improved by use of VIF tarps.

Since the 1998 report, little progress has been reported on environmentally sound ways to dispose of agricultural films after use in a soil fumigation, especially with regard to air quality, environmental and health issues should the films be burned. While recycling and biodegradable plastics would likely ameliorate the disposal process, no breakthroughs have been reported since the last MBTOC report regarding the difficult issue of recycling the combination of plastics used in VIF.

8.3.4 Other factors affecting emissions from soils

Irrespective of what surface barrier is used to trap MB, there are a number of key factors which affect emissions of MB during soil fumigation.

8.3.4.1 Soil characteristics

Studies of MB degradation in various soil types have shown that soil type greatly affects degradation, depending upon the time the MB is held in the soil. High organic matter and soil water content and increasing bulk densities are major factors which assist reduction in emissions (Gan *et al.* 1997, Thomas 1998).

8.3.4.2 Fumigation period

Tarps left on soil for longer periods increase the resident time MB is in the soil, thereby decreasing emissions. Wang *et al.* (1997a) demonstrated that emissions were reduced from 64% (PE 5 d) to 37.5% (VIF 5 d) and from 56.4% (PE 10 d) to $<3\%$ (VIF 10 d) in a sandy loam soil.

8.3.4.3 Irrigation

MB emissions can be reduced if the air filled porosity of the soil is reduced by increasing the water content. The presence of water increases the hydrolysis of MB to bromine ions. Irrigation reduces the variability in the distribution of MB in the soil, thus achieving a more reliable fumigation result (Wang *et al.* 1997a).

8.3.4.4 Organic amendments and fertilisers

It has been shown that the addition of nitrogen fertilisers and organic amendments enhance degradation of MB. Lime, ammonia fertiliser and ammonia oxidation bacteria increased the degradation rate of MB in soil (Ou *et al.* 1997, Gan 1997). These products have been shown to enhance degradation of MB. However, further research is required to identify their use for emission reduction.

8.3.4.5 Soil surface structure

A light rolling (pressing) of soil immediately after shank application closes furrows and seals the soil surface. This decreases direct emission from the injection points (channelling) within the first 24 hours after application and may assist reduction of total emissions (Anon 1997).

8.3.4.6 Formulations

A major reduction in emissions can be achieved by using formulations with lower concentrations of MB. Formulations with less MB but with chloropicrin (67:33) decrease MB doses to soil and therefore reduce MB emissions.

8.3.4.7 Dosage rates

Using VIF films and 50% of the normal MB dosage rate (between 140 and 250 kg ha^{-1}) similar control of nematodes, weeds and fungi have been achieved compared with full rates (280 to 500 kg ha^{-1}) using PE barrier films (Anon 1997, Gamliel *et al*. 1997, Yates *et al*. 1997).

In some countries (e.g. the USA) the potential for reducing MB dosages for soil fumigation compared to many other countries will be less because dosages are already low. In 1994 estimates of rates of MB used for soil fumigation in many European countries was between 50–100 g m^{-2}; in the UK 75–100 g m^{-2}; compared to rates as low as 20 g m^{-2} in regular use in the USA (Thomas 1998). Recent regulatory restrictions have reduced these high rates in several countries, such as in Spain in 1998 when rates were reduced from 50–80 g m^{-2} to 40 g m^{-2}.

Emissions have also been effectively reduced through adoption of mixtures of MB with other fumigants, notably chloropicrin in place of 100% or 98% MB.

Table 8.3 Percentage emissions of MB from a sandy loam soil following application using buried drip tubes

Barrier film status and authors	**Days after MB application**			
	5 days		**10 days**	
	Depth of application			
	25 cm	**60 cm**	**25 cm**	**60 cm**
Wang, Yates, Ernst, Gan, Gao and Becker, 1997				
Bare soil	87	60	-	-
PE film	59	15	-	-
VIF film	42	< 15	-	-
Wang, Yates, Ernst, Gan and Jury, 1998c				
PE film	64	-	56	-
VIF film	37	-	< 3	-

Note: Estimates of MB emission % using ion chromatography are made from determining the concentration of bromide ion remaining in soil after 42 d (Wang, Yates, Ernst, Gan and Jury 1998c) or 133 d (Wang, Yates, Ernst, Gan, Gao and Becker 1997) following MB application.

8.3.4.8 Depth of injection

Emissions of MB can be reduced by injecting the material deep into the soil. The extent of the reduction depends upon soil conditions. For example, in field and laboratory studies, increasing the depth of injection from roughly 25 to 60 cm resulted in a 40% decrease in emissions under tarped conditions (Yates *et al.* 1996). In laboratory studies, it was shown that increasing injection depth delays the occurrence of maximum volatilisation flux and also decreases cumulative emissions (Gan *et al.* 1997). The deeper the MB is injected the lower the emissions. At 25 cm, a depth which approximates industry standards for most crops, emissions ranged between 27 to 89% and at 60 cm emissions ranged between 3 to 21% (Table 7.3). Deeper shank injections increased the path distance, thus increasing the residence time for degradation (Wang *et al.* 1997ab) and minimising emissions.

8.3.4.9 Broadacre vs. bed

Strip fumigation can reduce the amount of MB applied by 20-40% as only the crop rows are treated rather than the entire field. This technique is common in tomato and strawberry crops. However, the ‘edge effect’ predominates and losses of MB from the edge of the bed tends to offset some of the advantages of strip fumigation, with regard to emission reduction.

8.3.5 Practices to reduce MB emissions from soil

There are a number of practices that could reduce MB emissions from soil treatments including:

- Limiting the frequency of MB fumigation by requiring intervals of 12–60 months between treatments. Alternative treatment methods could be implemented in the intervening period such as IPM, steam, solarisation, alternative fumigants and predatory fungi treatments. Reductions of 17–50% are feasible by implementing a reduction in fumigation frequency (refer to Table 8.1 in Anon. 1997). Reductions of >75% are feasible when other methods of pest control are used in combination.
- Use of MB only when pests are shown to be present at potentially damaging levels. In the UK, diagnostic tests are available for *Verticillium dahliae, Pythium* spp. and *Plasmodiophora brassicae* and diagnostic tests are being developed for the *Rhizoctonia solani* fungi; in New Zealand, indirect tests have been adopted for monitoring replant diseases using old season root stock and soil and comparing against a healthy standard; nematodes and pathogens are monitored in the USA; in South Africa proof of diseases is needed in order to use MB in orchards.
- Imposing permit systems which could ensure that only technically necessary fumigation would be carried out (e.g. The Netherlands in 1981). The criteria for permits could be proof of: (a) disease present and (b) that other pest control options have been examined. An organisational structure is needed to support this.
- Reducing doses by combining MB with other treatments in addition to VIFs, e.g. solarisation or biological controls (see Chapter 4 - 'Alternatives to Methyl Bromide for Soil Treatments').
- Adjusting pesticide controls, e.g. Italy in 1994 reduced the maximum dose to 60 g m^{-2} and in 1998 Spain introduced a maximum rate of 40 g m^{-2} and 20 g m^{-2} when used in combination with VIFs. Anon (1997) indicted substantial emission reductions if pesticide authorities reduced permitted MB doses (usually 50–60%).
- Regulate the users of MB to contractors only and licence and train operators responsible for fumigation.
- Where possible, shift practices from 'hot gas' methods using high concentrations of MB to soil injection that uses mixtures of MB/chloropicrin at lower MB concentrations, or substitute other chemical and non chemical treatments.

8.4 Structural and Commodity Fumigation

Post-harvest disinfestation of perishable commodities using MB is performed in fixed-wall structures such as fumigation chambers, or under gastight tarpaulins.

Controlled conditions allow manipulation of the key fumigation parameters: dosage, temperature and time. Greater control is potentially more achievable in an enclosed structure than in relatively uncontrolled field situations. The dosage can be reduced by increasing either the temperature or the time, or both, providing the commodity is able to tolerate the conditions. Forced air circulation allows reduction of the dosage through reducing the range of dosages experienced within the enclosure and thus reducing the need for high dosage rates. Developing high temperature schedules, with or without longer fumigation durations, could also reduce MB use providing the marketability of the produce is acceptable.

Improving the gastightness of fumigation facilities will minimise leakage of MB into the atmosphere. Simple test criteria have been available to the industry for determining the gastightness of chambers (Bond 1984) and these are part of the mandatory fumigation requirements for export of many perishable commodities.

More accurate measuring equipment to weigh MB will minimise excessive use of MB. This equipment could also be attached to equipment used for fumigation from small cylinders (e.g. 5 kg) and would avoid the use of small cans (about 1 kg). A system for decanting weighed dosages of MB from stock cylinders to small receivers for precise dosing of enclosures has recently been developed.

A combination of gases e.g. MB with carbon dioxide and phosphine, allows a reduction in MB, is less phytotoxic to cut flowers and ornamentals than MB or phosphine alone and has the same insecticidal activity. Reduced emissions can also be achieved by using reduced MB dosages in combination with carbon dioxide and/or heat. The MAKR™ system (Sansone 1994) is an alternative treatment that combines MB and carbon dioxide to reduce MB dosage from 24–36 g m^{-3} to 8 g m^{-3}. By adding 10% carbon dioxide, the amount of MB required is reduced by 50–66%. The carbon dioxide is heated, expanded and introduced into a structure with MB. The effects of carbon dioxide are twofold: it provides more efficient dispersion of MB into all parts of the structure; and increases the toxicity of the MB, perhaps by increasing the respiration rate of insects, reducing the amount of MB needed to eradicate the infestation.

8.5 Fumigant Recapture

Currently, with most fumigation systems, MB is released into the atmosphere at the end of the fumigation period. Technologies capable of capturing the MB that would otherwise be vented are now available commercially, but are in limited use. These recovery systems would allow most of the gas which would otherwise be deliberately vented to be captured for subsequent fumigation operations or for destruction.

The potential for recovery is limited by the loss of applied MB from reaction to give non-volatile products, by leakage and by efficiency of recapture.

Practically, the scope for recovery of MB after fumigations is likely to be restricted to treatments carried out in enclosures, i.e. space fumigations of commodities, structures and transport, with subsequent destruction of the captured MB. At this time no system for recovery of MB from soil fumigation has been commercialised and there are no systems known to MBTOC under development. Furthermore, since the phaseout of MB for soil uses in non-Article 5(1) countries is imminent (2005), such systems are unlikely to be developed.

In 2000, total space (durables, perishables and structures) treatments in Article 5(1) and QPS uses in non-Article 5(1) countries used 11,000-12,700 tonnes

MB. On the basis of 70% recapturable MB, this corresponds to about 8,000 metric tonnes of emissions that could be prevented from entering the atmosphere by the fitting of recapture and destruction equipment. There may be some additional potential for recapture for those contained applications of MB in non-Article 5(1) countries deemed 'critical' by the Parties.

8.6 Containment

The aim of containment in the use of MB for the fumigation of structures is to enable reduced dosages to be effective and to reduce emissions to the atmosphere. Containment alone would not normally be considered as a viable possibility to reduce emissions to the atmosphere without effective recovery technology. However, improved containment and monitoring may in fact be considered as a strategy for reducing emissions from structures while maintaining efficacy.

Containment and emission reduction strategies for structures involve: leakage control; extending the fumigation period, while ensuring adequate *ct*-products are achieved; and pressure testing. This aspect of fumigation can be enhanced by improved monitoring of fumigant concentrations and adjusting dosages where they are excessive.

8.7 Transfer of Knowledge and Training

Programmes for transferring knowledge and training is an essential component of a successful transition aimed at reducing MB use and emissions and/or to replace MB with alternatives and substitutes for structural pest control.

The mechanisms for transferring knowledge for many substitutes and alternatives are already well established in developed nations, where extensive information is readily available in existing texts and other resource materials. New ideas and technologies are disseminated through industry journals and conferences. Some manuals specifically detailing best practice for MB use are available (e.g. AQIS 2001).

Particularly crucial to lessening or eliminating MB for structural pest control is training for pest identification, monitoring and utilisation of new technologies. Programmes for training pest control managers and personnel in Article 5(1) countries should be tailored to social and cultural conditions, pest species and structural situations and to provide human health and environmental protection in each region.

8.8 Emission Reduction - Absorption Systems

A number of techniques have been proposed or investigated for their potential to partially or completely recover or capture MB from fumigation operations and some are now in limited commercial use. Depending on the technique used, recovery can lead to the MB either being emitted to the atmosphere at some later stage (e.g. during regeneration of the adsorbent or degassing if the used adsorbent is buried in a landfill), being recycled within the fumigation facility (discussed in this section) or being destroyed (discussed in the following section).

For technical or economic reasons only three recovery and recycling techniques are currently in commercial use at the time of writing this report. These are: (1) adsorption onto active solid substrates such as activated carbon; (2) refrigeration and condensation; and (3) between-chamber transfer. Several others are being actively researched.

If containment and recovery are to be specified as the means of reducing MB entering the atmosphere, it will be necessary to define the maximum permissible quantity or concentration that may be emitted. This will allow specification of efficiencies required for recapture equipment.

8.8.1 Activated carbon

Activated carbon can adsorb relatively large amounts of MB, up to 30% by weight, depending on activated carbon type and conditions. It is widely used throughout the world to remove trace amounts of organic contaminants from gas streams.

For fumigation operations, a vessel containing activated carbon is installed in the gas vent line. At the end of the fumigation treatment, the gas mixture containing MB and air is passed through the activated carbon onto which the MB is adsorbed. The proportion retained on the activated carbon depends mainly on the amount of free activated carbon available. The rate at which it adsorbs depends on the concentration in the gas stream, gas flow rate, activated carbon characteristics and temperature. At a low MB loading, a MB recovery rate close to 100% is achievable. However, for most systems, some MB will be emitted to the atmosphere.

Eventually the adsorption capacity of the activated carbon is reached and it needs to be regenerated or disposed. Regeneration can be achieved by passing hot gas over the activated carbon and could be the basis of a reclamation process. Alternatively, the activated carbon and MB can be incinerated in a specialised facility. However, concerns about emissions of toxic chemicals may prevent this from being a viable option in some locations.

Although there has been much research into the potential use of activated carbon with MB, there are only a few known commercial fumigation installations worldwide that have, or have had in the past, activated carbon beds installed to recover MB. There are chambers in the Netherlands, each with a 70 kg filter of activated carbon. With these chambers fumigation at 30 g m^{-3} is carried out and a 40 - 50% recovery is achieved. The activated carbon lasts for 40 fumigation operations and the spent carbon containing the adsorbed MB is incinerated in a special incineration facility. There is also a 30 m^3 chamber in Thailand fitted with a 72 kg bed of activated carbon. The chamber is used for fumigating asparagus and green okra exported to Japan. The system is capable of reducing MB concentrations in the vented gas to 5 ppm within 30 minutes. The fully absorbed activated carbon is disposed of in a sanitary landfill.

An activated carbon system has also been developed by Rentokil UK for use with their fumigation bubble, a well-sealed plastic tent enclosure used for fumigation of small structures. A 10 kg activated carbon bed which can hold up to 1.5 kg MB (equivalent to 5 fumigation cycles) is used. Regeneration of the activated carbon is achieved by blowing hot air through the beds. This results in direct emissions to the atmosphere. However, its use was intended only to prevent emissions that might endanger people in the immediate vicinity of the fumigation operation not as a means of preventing emissions to the atmosphere.

Although activated carbon systems provide the most immediate opportunity for reducing MB emissions, they have usually only been considered for very small facilities where commodities or structures are fumigated and where, for reasons of protecting the immediate surroundings, very low concentrations of MB are permitted. Very large activated carbon beds containing tonnage quantities of carbon would be required for the fumigation of large structures or enclosures such as mills, grain silos or tarpaulin fumigation. Unless the MB is directly recovered for direct reuse, once the activated carbon has been fully loaded it will be necessary to remove the carbon for disposal or regeneration in an appropriate manner. In some regions there may be limitations on the off-site transport of adsorbent loaded with MB.

A process recently developed in the USA uses activated carbon to capture MB followed by thermal destruction (Knapp *et al*. 1998, Leesch *et al*. 2000). Two units are now in commercial operation, described further below.

Two plants associated with quarantine fumigation facilities in the Los Angeles port area in USA are equipped with carbon bed absorption systems to prevent MB discharge into the local environment to meet local air quality regulations. Both these facilities treat a diverse range of commodities, including export cotton, using vacuum fumigation. Cotton is typically treated at a high dosage rate (144 g m^{-3} MB), making reclamation a feasible process. The plants were commissioned in 1993 and 1996.

It is technically possible to recycle MB adsorbed on activated carbon by heating the carbon, traditionally by passing hot air over it, or by altering the pressure (temperature and pressure swing adsorption). Circulating air strips that desorb MB from the activated carbon and the mixture can potentially be reintroduced into the fumigation chamber. The MB is reclaimed as a high concentration mixture in air suitable for direct reuse as a fumigant, but some topping up will be necessary to compensate for system losses so as to achieve a satisfactory fumigation concentration.

Pilot scale studies have demonstrated the technical feasibility of such a process (Smith 1992) with up to 95% of the recoverable MB being available for direct reuse. One of the Los Angeles installations apparently is able to reuse recaptured, desorbed MB from the carbon beds.

There have been concerns about the purity of recycled MB and, in particular, whether there will be build-up of other gas phase impurities with multiple recovery cycles that may be of concern from product quality Also there is concern that reused fumigant will achieve certification or approval from regulatory authorities and the original manufacturers of the MB. Developers of recycling technology have also encountered technical difficulties in designing equipment to perform the recycling step within the time constraints placed on commercial fumigation operations. Activated carbon is now receiving more attention as a means of capturing MB after fumigation for subsequent destruction.

8.8.2 Zeolite

Zeolites are a special type of silica-containing material which have a porous structure that make them valuable as adsorbents and catalysts. They are found naturally and can also be manufactured to precise specifications. Processes based on the use of zeolite adsorbents to remove CFCs from vented air streams are in commercial use.

Although zeolites are more expensive than activated carbon, they have high adsorptive capacity, particularly at low concentrations. They can be manufactured to very narrow pore size distribution tolerances for specific applications and it may be possible to avoid any potential problems of contamination of the recovered MB with other volatile compounds, by utilising the selective sorption that is conferred by a particular pore size range.

Pilot scale demonstration trials of the recovery and direct recycling process were conducted in July 1994 in Washington State, to demonstrate the technical feasibility of the technique for recovering MB from cherry fumigation operations. Recovery in excess of 90% was achieved (Nagji and Veljovic 1994). Analysis of the recycled MB showed no other volatile compounds from the fruit were released. However, these tests needed to be confirmed over a large number of adsorption/desorption cycles.

A similar small recovery plant was installed and successfully commissioned at a fumigation facility in Chile. Recoveries of more than 94% of the MB from the fumigation chamber and recycling rates of 87% were achieved. At the time of preparation of this report, approval had not been granted by USA authorities for the quarantine treatment of grapes using recycled MB.

In an improved version of this process, that has been altered so that direct recycling is no longer necessary, the captured MB is recovered from the zeolite bed and refined in an off-line step. The MB is potentially available for other fumigation operations (Willis 1998). This change significantly reduces the complexity of operation of the recovery plant because it is no longer necessary to have complex or expensive analytical equipment to measure MB concentrations as there is no direct recovery and re-injection into the fumigation operation.

The process of MB capture has been demonstrated on diverse operations such as fumigation of an empty ship hold, shipping containers and a lumber warehouse (Weightman 1999). Data from the ship hold trials indicate that the process is capable of capturing up to 90% of the applied MB (Fields and Jones 1999). No information has been published on the success of the recycling component of the technology. It is intended that zeolite reprocessing to capture MB for recycling will take place in Nevada, USA and the technology is now being promoted in North America, but has not yet been taken up by a commercial operator. It would be difficult for the technology to be adopted in other parts of the world unless other reprocessing sites were established.

An issue with this process, and any other aimed at recycling MB, is whether the recovered MB is sufficiently pure to be able to be reused as “pure MB” to comply with the specifications for established quarantine schedules and whether it can meet the labelling requirements of individual countries to be sold as MB for any permitted use. Recycling processes have the potential to provide a means of reducing emissions from a range of fumigation operations, and making MB available for uses where MB alternatives are more difficult to implement.

To MBTOC’s knowledge, zeolite-based processes are not in current use. Zeolites offer a better opportunity for recycling compared with activated carbon because of the specificity of the adsorbent, thus avoiding the potential for contaminants in the reclaimed MB, though the adsorbent capacity is lower than for activated carbon.

8.8.3 Condensation and activated carbon

One of vacuum fumigation plants in Los Angeles, referred to above, uses condensation to reclaim some of the MB when high concentrations of MB are being used, followed by absorption on carbon of the residual gas. MB is stripped from the carbon using a vacuum process and is reused. The fumigation plant with its condensation and activated carbon recovery system apparently meets the local air quality requirements. Access to the plant is restricted and no data have been supplied to determine the level of recovery or recycling.

8.8.4 Refrigeration and condensation

A pressure/cooling condensation process is in use in California USA to recover MB, where it is in a highly concentrated form in the vent gas lines from cylinder filling at a bulk handling facility.

8.8.5 Between-chamber transfer

At sites where there are multiple vacuum chambers treating large quantities of commodities there is the opportunity to reduce the amount of MB being emitted to the atmosphere by transferring the MB that would otherwise be vented at the end of a fumigation treatment to an adjacent chamber where a treatment is about to commence. This process needs equipment for accurate and rapid measurement of MB concentrations to be available so that the 'topping up' dose required to compensate for MB lost through adsorption into the commodity and through reactive breakdown can be calculated. This technique is used at a fumigation facility in the Ivory Coast (Dosso 1998).

8.8.6 Technologies under development

Research in Japan has led to the development of a new adsorbent called MBAC that is a mixture of activated carbon and special substances (amines) which have a greater adsorptive capacity for MB than activated carbon alone. This material can be produced as sheets and introduced into packaging to recover the slowly desorbing MB from fumigated commodities and also has potential to recover some MB from soil fumigations. A granular and a sheet product have been developed for use in adsorbing the MB that is slowly emitted after a fumigation treatment (Kawakami and Soma 1995). The Japan Methyl Bromide Industries Association has conducted evaluation tests (Muraoka T., pers. comm. 1998). Efforts are now being made to develop domestic markets for the product. There are no details available on techniques for disposing of the contaminated adsorbent.

8.9 Emission Reduction Through Recovery and Destruction

8.9.1 Adsorption into reactive liquids

MB can be destroyed by reaction with ammonium thiosulphate (Gan *et al.* 1998). Recovery and destruction systems are now being sold (Nordiko 2001) based on MB capture from fumigation operations using activated carbon followed by destruction of the MB and regeneration of the activated carbon using thiosulphate. Commercial units are in use at several ports in Australia. The recovery/destruction units are designed to be clip-on units for fixed or container-based fumigation installations and are completely self-contained. No further or off-site processing of the spent carbon is required. The process for capture of MB is similar to all activated carbon processes. Once the beds are fully exhausted, they are removed and treated by immersion in sodium thiosulphate. The activated carbon beds are prepared for reuse by rinsing and drying in air at 40 C.

Amines typically react with MB to give methylated non-volatile products. A system based on organic amines and alkali for removing residual MB from fumigated 28 m^3 freight containers in Russia has been described (Rozvaga and Bakhishev 1982). No information was available to MBTOC on whether this system is in current use. Mordkovich *et al.* (1985) have also described a technique using aqueous sodium sulphite as a neutraliser and a mixture of ethylene diamine and sodium carbonate as an adsorbent. Again, it is not known whether these techniques have achieved general use.

Research was carried out in the 1970s with a technique for liquid scrubbing to remove MB from fumigation operations (Anon 1976). The process was developed and tested on timber fumigation under stacks and consisted of equipment to circulate MB and air from the fumigation enclosure through a tank of aqueous monoethanolamine (50%) and back to the fumigation tent. The process achieved 70% reduction in MB concentrations, but was slow taking 40 - 60 minutes to achieve this level of reduction. The size of the necessary equipment for full scale operation and the difficulties of handling the contaminated liquid material have prevented commercial development.

8.9.2 Destruction using ozone

One of the Los Angeles vacuum fumigation plants, referred to above, uses ozone to destroy the MB in discharge and air washes from the vacuum chambers. Activated carbon is used to scrub any residual traces of MB from the discharge air stream. At the date of writing, results from two monitored trials indicated that in excess of 90% of MB used is destroyed. The destruction plant is large and has a significant electrical power requirement for the ozone lamps and the blowers. Thermal and catalytic destruction

A process recently developed in the USA uses activated carbon to capture MB followed by thermal destruction. The intention of developers has been to provide a supply and disposal service by transporting the MB-laden carbon to a central processing site where it would be reprocessed or destroyed (Knapp *et al*. 1998, Leesch *et al*. 2000). A small commercial unit is in operation at Dallas/Fort Worth airport capturing MB from quarantine operations (McAllister and Knapp 1999) and a larger unit is installed and has operated for tow complete cycles at a commercial berry fruit exporter's site in Watsonville, California (Knapp 2001). Both plants reduce the MB concentration in the fumigation chambers down to a level of 500 ppm before venting the remainder. Once each plant has processed sufficient MB to fully load the activated carbon beds, they are shipped to Pennsylvania to be incinerated. Preliminary data suggested that in excess of 95% of the MB being vented could be removed. After allowing for MB lost by adsorption into the commodities being fumigated, the Watsonville plant has achieved a recovery of 80% of the original dose applied.

Previous indications were that the cost of a complete MB supply and removal service would be about 7 times that of the MB price at that time, but on a per unit basis for commodity treated, the price may be affordable (Leesch 1998). One of the critical features of this process is the environmental impact (truck fuel, energy use) of transporting equipment containing the activated carbon beds saturated with MB over some distance to the reprocessing or destruction plant. This technology will have different cost implications in other parts of the world compared with continental USA.

There is present research in Japan on the catalytic decomposition of MB. Promising recent results from using new Mn/Cu-zeolites indicate that satisfactory levels of destruction can be obtained at lower temperatures than previously achieved and the production of CO will be minimised. This research is still at an early stage of development.

New research from Japan has been reported in which MB that has been previously captured on activated carbon or zeolite is introduced to a reactor heated to 400 – 500 C and decomposed with CaO to inorganic salts (Yahata *et al.* 2001). A bench scale apparatus has been described that gave MB concentration reductions of 99.99%.

8.10 Emission Reduction through Modification of Treatment Schedules

MBTOC has suggested previously that Parties encourage their Regulatory Authorities to review their current treatment schedule requirements and confirm that the minimum amount of MB required to control quarantine pests are in practice. Recent research has shown that MB dose reduction is possible while still controlling quarantine pests. For example, cut-flowers from Israel consist of many different species, each with differs in tolerance to MB and each with a range of pests of quarantine concern to overseas markets. The MB dose could be reduced to avoid phytotoxicity by 2-2.5 times compared to previous schedules while at the same time controlling three of the main quarantine pests (Kostyukovsky *et al.* 1998).

However, efforts at dose-reduction may be negated by other research that continues to increase the dependency on MB. For example, research is still being commissioned in Australia, the USA and other countries to develop MB-based treatments for export crops to Japan that will continue to add to the amount of MB consumed for quarantine and pre-shipment treatments. For example, Californian 'D'Agen' plums could be exported to Japan in the future following the results of research that showed treatment with MB at 48 gm^{-3} for 2h at > 19°C to control codling moth (Leesch *et al.* 1999). In order to compensate for absorption of the gas by the packaging, the MB dose was approximately twice that required to control the most resistant stage of codling moth. This treatment is similar to MB treatments on cherries, apples and walnuts nectarines exported to Japan from a number of countries including the USA, Australia, New Zealand and France.

Mixing MB with other gases such as pure phosphine may also allow a significant reduction in MB concentration. For example, satsuma mandarins (*Citrus reticulate*) fumigated with MB, phosphine and a mixture of MB and phosphine. No injury was observed on fruit at 48 g m^{-3} of MB for 2 hours at 15, 20 and 25°C and mixtures of 14 g m^{-3} of MB and 3 g m^{-3} of phosphine for 3 hours at 20°C (Akagawa *et al.* 1997). However, waxed fruit were damaged when fumigated with the mixture. This research demonstrates that half the dose of MB could be feasible compared to the use of MB alone.

8.11 Drivers for Adoption of Recapture of MB

The clip-on units for container fumigations and MB recapture and destruction may be an exception. At present , despite Decisions VII/5(c) and XI/13(7) that urge Parties to adopt MB recovery and to minimise emissions for QPS MB treatments, there are no installations known to MBTOC that have been installed specifically for ozone-layer protection. However there are increasing numbers of installations, based on active carbon systems, that are designed to recapture MB after well-contained commodity treatments. These units are being attached to MB fumigations in port areas and other urban environments to scrub emissions from fumigations to comply with local regulations for toxic gas emissions, air and environmental quality and worker safety.

Most of the recovery technologies mentioned above and all the recycling technologies are complex in nature. In many cases, they are likely to be a significant part of the total cost of a fumigation facility and to have significant running costs compared with costs of treatments. At present MB prices, reclamation of MB for reuse is unlikely to be justifiable economically, though it may become so in future with constrained MB availability and improvements in recapture technologies.

The recent development of clip-on units for recapture and destruction of recaptured MB for container and similar treatments opens the way for recapture at reasonable cost for QPS fumigations.

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Chapter

9

Case studies on commercial adoption of alternatives to MB

9.1 Introduction

This chapter contains a compilation of case studies prepared by MBTOC members or requested from national experts and reviewed by MBTOC, relevant national experts and others. The case studies are grouped below into three categories, relating to MB alternatives for production of fruit and vegetables, for ornamentals and tobacco, and for postharvest uses. A short summary describing the alternative has been included.

Case studies are included in this Assessment Report to provide data on alternatives, particularly implementation of alternatives, where the standard publication literature is insufficient and additional detail is useful. MBTOC preferred to rely on openly published and refereed documentation to substantiate information in this Report, but recognised that in the agricultural sector such documentation was not always available. This is particularly so where an alternative is being applied in practice.

9.2 Case studies on alternatives to MB for soil uses - fruit and vegetable production

CS 1. Use of 1,3-dichloropropene + chloropicrin + herbicide as MB alternative in tomato and pepper production in Florida (USA)

CS 2. Use of biofumigation + solarisation as MB alternative in tomato and cucumber production in Macedonia

CS 3. Use of glyphosate, metham sodium and IPM for control of Moko disease of bananas in Colombia

CS 4. Use of grafting and metham sodium as alternatives to MB for the control of soil-borne pathogens in tomatoes grown under plastic tunnels in Morocco

CS 5. Use of IPM as MB alternative in the production of vegetable crops in France

CS 6. Use of metham sodium and solarisation in tomatoes and peppers in Uruguay

CS 7. Use of non-chemical alternatives to MB in vegetable production in Uruguay

CS 8. Use of seedtrays as MB alternative for tomatoes in Brazil

CS 9. Use of solarisation as MB alternative for melon production in Costa Rica

CS 10. Use of solarisation as an alternative to MB for the control of broomrape (O*robanche ramosa*) in melon under plastic tunnel conditions in Morocco

CS 11. Use of solarisation and IPM for tomatoes and peppers in Florida and Southeastern USA

CS 12. Use of natural substrates as MB alternative for strawberries in UK

CS 13. Use of substrates used as MB alternative for strawberry production in greenhouses in the Netherlands

CS 14. Use of substrate systems as MB alternative in tomato and pepper production in Hungary

CS 15. Use of substrates and *Trichoderma* as MB alternative for tomatoes in New Zealand

CS 16. Use of soil-less tomato production as MB alternative in Belgium

Case study 1. Use of 1,3-dichloropropene + chloropicrin + herbicide for tomato and pepper production in Florida (USA)

The combination of 1,3-dichloropropene + chloropicrin and herbicides, sometimes with an additional application of chloropicrin, has been shown to be an effective alternative to MB for tomato and pepper when the fumigant mixture is applied using deep placement coulter equipment

Crops

Fresh market tomato and peppers

Target pests

Nematodes: *Meloidogyne* spp.
Rotylenchulus reniformis
Pathogens: *Fusarium oxysporum* f. sp. *lycopersici*, races 1, 2 & 3
Fusarium oxysporum f. sp. *radicis-lycopersici*
Sclerotium rolfsii
Pythium myriotilum and *P. aphanidermatum*
Weeds: *Cyperus rotundus* (purple nutsedge)
Cyperus esculentus (yellow nutsedge)
Portulaca oleracea (purslane)

History

Florida State is the largest producer of fresh market tomato and pepper in the United States. In the 2000/2001 production season, about 17,520 and 7,440 ha of tomato and pepper, respectively, were harvested in Florida. Soil fumigation with MB has been an important component of the Florida production system since the early 1970s. The development of alternatives was started in the 1990s in response to the Montreal Protocol controls on MB. Initial trials using traditional application methods for 1,3-dichloropropene + chloropicrin ('Telone C-35') such as parachisels or swept back shanks did not provide satisfactory results. The system was made effective by using equipment originally designed for conservation tillage systems (the deep placement coulter system) to inject the fumigant, and by teaching growers proper methods for the application and incorporation of herbicides into soil.

Commercial use

The combination of 'Telone C-35' + herbicides is now used by a number of tomato and pepper producers in Florida as a MB alternative. It is used by growers who previously relied exclusively on MB. In the 2001/2002 growing season, about 1,298 ha of commercial production fields were treated with this alternative system. About 50% of the farms were able to produce a second crop in the treated fields after completion of the first crop without additional applications of soil fumigants. On several farms, the alternative system has been used for three consecutive years without a loss in efficacy or increase in the build-up of soil-borne pests (Mirusso 2002).

Description of alternatives

The combination comprises 61% 1,3-dichloropropene + 35% chloropicrin ('Telone C-35') + herbicides, sometimes with an additional application of chloropicrin. This alternative system is applied by the growers with technical assistance from several commercial fumigation companies, pest management specialists from the University of Florida and USDA-ARS, and Dow AgroSciences.

Telone C-35 is applied to soils that have been disked and sealed with a roller using a deep placement coulter system that minimizes disturbance to the soil. The fumigant is applied to a depth of 25 cm using injection knives placed 30 cm apart. Application rates are typically 1.9 litres per ha. Herbicide applications are made either in advance of the Telone application or immediately before the plastic mulched beds are prepared. Herbicides typically used include napropamide ('Devrinol') and trifluralin ('Treflan'). During the autumn production season, when pest pressure is more intense, an additional application of chloropicrin may be made in the planting beds prior to covering with plastic mulch.

When application of chloropicrin in the bed was added to the system, pest control levels similar to those in adjacent areas fumigated with MB were achieved consistently, including the control of yellow and purple nutsedge, both major problem weeds with many systems, including MB. Tomato and pepper yields were statistically similar to yields in MB fumigated soils, and in some cases the alternative system provides higher yields. Uniform incorporation of the herbicide was found to be essential to avoid early season phytotoxicity and so ensure adequate yields. The large-scale demonstrations, validation trials and commercial results have confirmed that this alternative system is technically feasible for the majority of fresh market tomato and pepper farms in Florida (Chellemi *et al*. 2001, Gilreath *et al*. 2001, Gilreath *et al.* 2002, Mirusso *et al.* 2002, Mirusso 2002).

Regulatory agency acceptance

Telone C-35 is registered for tomato and pepper in Florida. It is also registered for these crops in California and other US states. The use of personal protection equipment (PPE) is required if workers in the field are exposed, but hot summer temperatures make the use of PPE for any length of time a safety issue. This problem can be addressed by applying the fumigant using a single operator in a fully enclosed tractor cab equipped with an organic filter. All fumigation companies applying Telone C-35 in tomato/pepper in Florida currently use such enclosed cabs so that the fumigant can be applied 7-10 days in advance of the bed preparation crew, thus removing the need for PPE for field workers. The majority of farmers applying Telone directly have at least one enclosed cab tractor with the proper filters. The two herbicides, Devrinol and Treflan, are registered for tomato and pepper in USA.

Were the treatments difficult to implement?

No.

Applicability to other crops and regions

Large-scale field validation studies using this alternative have been completed on strawberry, watermelon, eggplant, and cucumber in Florida and have resulted in pest control levels similar to adjacent fields treated with MB. This system is also being used by commercial producers of fresh market tomato, pepper, strawberry, watermelon, cantaloupe and cucumber in Georgia and South Carolina (Mirusso 2002). This alternative is technically feasible for tomato, pepper, eggplant, strawberry, and cucurbit production in the southeastern and Midwestern United States and has been made available to growers in those regions through demonstration trials, extension talks, and popular press articles in the last three years.

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Case study 2. Use of biofumigation + solarisation as MB alternative in tomato and cucumber production in Macedonia

The combination of biofumigation + solarisation substantially reduces the time required for solarisation alone. Moist soil is mixed with organic material, well incorporated in the soil to a depth of 20 cm.

Crop	Greenhouse tomato and cucumber	
Pests	Nematodes:	Root-knot (*Meloidogyne* spp.)
	Pathogens:	*Phytophthora* spp., *Pythium* spp., *Rhizoctonia* spp., *Fusarium oxysporum, Verticillium dahliae, Alternaria alternata* and others
	Weeds:	Various species

History

Macedonia produces vegetables on an area of about 56,000 ha. About 19,000 tonnes of vegetables are produced in greenhouses annually. Two production cycles take place each year so that crops are ready for harvest when market prices are highest. MB is used for common soilborne pest problems such as nematodes, pathogenic fungi and weeds. A Multilateral Fund project trialled various alternatives in 1999-2000 in an area of about 36 ha. Biofumigation + solarisation was found to be both effective and cost-effective.

Commercial use

Biofumigation + solarisation is used commercially on a number of farms and an extension programme is underway to enable widespread adoption in the horticultural regions of Macedonia.

Description of alternative

The combination of biofumigation + solarisation substantially reduces the time normally required for a solarisation treatment. The process in Macedonia consists of mixing moist soil with organic material, such as cow manure and straw, applied at 5-7 kg m^{-2} and well incorporated in the soil to a depth of 20 cm. The soil is irrigated with 30 mm of water and covered with a transparent polyethylene sheet. The organic matter decomposes and raises the temperature to about 45-50°C, even up to 70°C, aided by solarisation. The treatment takes 2 – 3 weeks in Macedonia's climate.

Growers find solarisation + biofumigation very acceptable because it gives good pest control, is relatively easy to handle, and provides fertilizer. The alternative treatment is cheaper and more profitable than MB (Popsimonova, 2002). The vegetable products are very acceptable to consumers. In comparative trials, the alternative treatment gave tomato yields of 126 compared to 114 tonnes per hectare for MB. Cucumber yields were 235 compared to 202 tonnes per hectare for MB (Popsimonova *et al*. 2001).

Regulatory agency acceptance

Solarisation and biofumigation do not require registration in Macedonia.

Were the treatments difficult to implement?

No.

Applicability to other crops and regions

This technique is currently used in several countries and can be adapted for use in other regions that have sufficient sunshine hours and temperature during the treatment period prior to planting, for certain disease or pest complexes and cropping systems (Medina-Mínguez 2002, López *et al*. 2002, Bello *et al.* 2002). Large local sources of suitable organic waste materials are needed. Biofumigation + solarisation is used for the commercial production of greenhouse pepper on more than 40 ha in Spain (López *et al*. 2002) and for the production of tomato and melon in Uruguay (see Case study 7).

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Case study 3. Use of glyphosate, metham sodium and IPM for control of Moko disease of bananas in Colombia

Diseased banana plants are killed with glyphosate (a herbicide), which significantly reduces bacterial populations since they are highly specific for their host. This practice is best used as part of an IPM program.

Crops Bananas and plantain

Pests Pathogen: Moko disease (*Ralstonia solanacearum* race 2)

History

Banana cultivation for export was begun actively in Colombia at the end of the nineteenth century and during subsequent years became established as one of the main agricultural activities. Production occurs in two main regions.

At present there are approximately 42,000 ha of bananas in Colombia providing over 28,000 direct jobs and more than 75,000 indirect ones. In 1997, Colombia exported 82 million boxes of bananas valued at $US465 million dollars. Banana plantations in Colombia are mostly composed of the Cavendish variety.

There are records of MB utilization in the banana growing zone of Urabá - Antioquia up to 1993 and until later in the Magdalena Province. MB has been used in banana and plantain crops to control Moko disease caused by the bacterium *Ralstonia (Pseudomonas) solanacearum* race 2. The disease was first reported in Colombia in 1954 and has since spread all over the main Colombian banana and plantain growing regions. Control initially involved specific practices, such as cutting off the acorn, eradicating plants and fumigating the soil with MB within a 5 to 10 metres radius around the source. However, it became apparent that integrating other prevention measures was necessary, such as using healthy seed (e.g. disease-free banana plants obtained by tissue culture), disinfecting tools, materials and machinery, strict weed control and adopting cultural practices that did not encourage disease dissemination.

Due to risks posed by this disease, the Banana Growers Association of Colombia AUGURA initiated a program for the identification, eradication and recording of Moko disease foci, with the mission of inspecting and controlling diseased areas, supervising control measures, and advising growers. AUGURA implemented sanitary brigades that over the years have ensured adequate control levels.

Current commercial use

The alternative is used by most growers in the Urabá region where MB was completely phased out in 1993. Growers in the Magdalena region are now adopting the system.

Continued training and supervision of growers is an essential component of the program.

Description of the alternative

This method requires close monitoring of banana plantations in order to detect diseased plants as soon as possible. Once the disease appears, affected plants as well as those within a 5 metre radius are killed with 50 to 60 cc of glyphosate (a broad spectrum herbicide), after which the plants are pulled out and the land is left bare during a 6 month quarantine period. Although the bacterial pathogen is not an obligate parasite, it does not survive well in the absence of its host and the moist soil associated with banana production. Therefore, after the quarantine period it is virtually eliminated. To ensure complete elimination some growers also apply metham sodium. In either case, it is very important for success to complement this system with IPM practices and strict sanitation. Weed control is essential, as it has been shown that the bacterium can survive on certain weeds without producing any symptoms.

Growers from the Magdalena region have preferred to continue using MB, arguing that it was more economical because it did not require the 6 month quarantine period. However, recent economic analyses have confirmed that the glyphosate method is the most cost effective alternative for controlling Moko disease of banana, taking into account the quarantine period. Dazomet is equally effective to MB and also similar in terms of cost and time (about twice the cost of glyphosate). Further, new research is being conducted on possible rotation with non-host crops (e.g. cassava, corn), so that the fallow period can be made productive.

Regulatory agency acceptance

Both glyphosate and metham sodium have been registered in Colombia for many years.

Were the treatments difficult to implement?

No, but they do require cooperative work among growers and also with their association and phytosanitary authorities. Adequate training of all persons involved is essential to the success of this alternative.

Applicability to other crops and regions

Banana growers in Costa Rica also use this system and since this country plays a leading role in banana production in Central America it is very possible that growers from other countries in the region will also adopt it. Growers in Ecuador are reportedly also using this system.

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Case study 4. Use of grafting and metham sodium as alternatives to MB for the control of soil-borne pathogens in tomatoes grown under plastic tunnels in Morocco

*Grafting tomato plants onto resistant cultivars plus application of metham sodium is an effective alternative to MB for the control of root-knot nematodes (*Meloidogyne *spp.).*

Crop

Tomato

Pests

Fusarium oxysporum f.sp. *lycopersici* (races 1 and 2), *Verticillium dahliae* (races 1 and 2), *Meloidogyne* spp.

History

Tomato is of great economic importance to Morocco. Soil fumigation with methyl bromide to control soil borne pests has been considered essential for the success of greenhouse tomato production. To decrease the use of MB, an Integrated Pest Management program including grafting and chemical control with metham sodium has been introduced.

Current commercial use

These alternatives, together with cultural practices such as sanitation, organic amendments, pathogen-free seeds and seedlings, weed control, and improvement of plant growing conditions, are widely used commercially.

Description of Alternative

Some cultivars are resistant to *Meloidogyne* spp. However, this resistance brakes down when temperature and nematode populations are high.. Therefore, grafting and metham sodium are used for both susceptible and resistant cultivars. Grafting, which was once considered too expensive, is now widely used by farmers, and grafted plants are available from commercial nurseries. In general, planting densities vary from 18,000 plants/ha for non-grafted plants to 9,000 plants/ha when grafted plants are used, but it is possible to obtain the same yields with either plantings. This happens because grafted plants are larger, and are trained to two stems instead of one. For soil disinfestation, metham sodium is applied through the drip irrigation system.

Regulatory agency acceptance

Tomato rootstocks, resistant cultivars and metham sodium are registered.

Were the treatments difficult to develop?

No.

Was the treatment difficult to implement?

Availability of grafted plants and drip irrigation system determine the feasibility of implementation.

Applicability to other crops and regions

Yes. The alternatives are also used for melon and cucumber.

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Information contributed by Prof. Mohamed Besri

Case study 5. Use of IPM as MB alternative in the production of fruit and vegetable crops in France

Horticultural producers in France use a combination of chemical and non-chemical methods for production fruit and vegetable crops. Increasingly, they are adopting IPM systems which make use of all possible resources - not just chemical control - to reduce and prevent the incidence and effects of diseases or pest.

Crop

Melon, strawberry tomato, cucumber

Target pests

Nematodes: *Meloidogyne* spp.

Pathogens: *Pyrenochaeta lycopersici* (corky root of tomato)
Verticillium dahliae (wilt)
Fusarium oxysporum f.sp. *lycopersici* (wilt)
F. o. f. sp. *radici*
Phomopsis scleroides (in melons)

History

Horticultural production in France is of an intensive, highly technical nature. The vegetable sector was valued at €2,234 million in 2000 and is plays an important role in the country's economy (Anon 2000). Since 1997, consumption of MB has declined due to three main reasons: a) International government decisions taken under the Montreal Protocol; b) Consumer demands for residue-free products of high quality which has resulted, for example, in the banning of MB use in lettuce production, and c) The high cost of MB at present, currently exceeding that of other available fumigants (Fritsch 2002). Integrated Pest Management (IPM) including soilless culture and grafting is providing growers with a new production approach to eliminate harmful pathogens and/ or avoid the need of fumigation.

Commercial use

Soilless culture is increasing significantly as a replacement to MB on tomatoes and strawberries. In 2001 a total production area of 3430 ha of tomatoes was reported, 37% of which is in the open field (no soil disinfestation required) and the rest in greenhouses (Anon 2001). Presently, about 950 ha (nearly 45% of greenhouse production) are in soilless production, mostly in the Northeast of France.

Over the last three or four years strawberry growers have also adopted soilless production systems reducing the amount of MB used for this crop by 90% (Fritsch 2002).

Grafting is also proving useful for tomatoes, melons and eggplant and is being used increasingly by growers. Soil fumigants, particularly metham sodium and 1,3-dichloropropene + chloropicrin (Telone) are also used as part of the IPM system.

Table CS5.1 provides a comparative analysis of the use of MB and alternatives in the vegetable sector in France showing substantial commercial adoption of alternatives.

Table CS5.1 Trends in soil disinfestation techniques in France 2000 (Fritsch 2002)

Soil disinfestation technique	**Hectares treated**	**Trend in use**
Dazomet	1,000	Stable – expensive
1,3-dichloropropene	7,000	Up
Metham sodium	4,000	Up – especially for strawberries
Methyl bromide	1,203	Down
Sodium tetrathiocarbonate	500	Up – especially for melons
Solarisation	200	Stable
Steam	2,000	Stable
Total	15,903	Up

Description of alternatives

In essence, IPM involves making use of all possible resources - not just chemical control - to reduce and prevent the incidence and effects of diseases or pest. Crop sanitation, disease-free plant material, physical and cultural controls, disease or pest resistant varieties, scouting for diseases and record keeping are included within IPM, contributing to pest reduction and leading to less usage of chemicals.

Soilless culture in France mainly employs a mixture of peat and pine bark or inorganic components, particularly in the case of strawberries.

The Agronomic Research National Institute has developed several tomato varieties suitable for grafting such as "Brigeor" which provides resistance to *P. lycopersici, Verticillium* spp.*, Fusarium* spp. and nematodes. "Beaufort" and "Maxi fort" also show good resistance to nematodes. Grafting is also used on eggplants to reduce susceptibility to *V. dahliae* and on melons against *Fusarium* and *Phomopsis* blight.

New and improved application techniques are making it possible for growers to use low doses of fumigants such as 1,3-dichloropropene + chloropicrin (Telone), metham sodium and others.

Regulatory agency acceptance

Chemical products appearing on Table 1 are presently registered in France. Other alternatives included in the IPM approach (e.g. substrates, grafting) do not require registration.

Were the treatments difficult to implement?

No, but growers need to adopt a different approach towards crop production, mainly requiring gathering information, keeping records to establish an action threshold and learning about target pests and diseases.

Applicability to other crops and regions

To many authorities, IPM presents a superior and long lasting solution to severe diseases and pests attacking crops (Fritsch 2002). IPM systems are used throughout the world in many climates, production systems, and crops, using different kinds of substrates.

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Case study 6. Use of metham sodium and solarisation in tomatoes and peppers in Uruguay.

Solarisation, combined with biofumigation or fumigants such as metham sodium, is more efficient than solarisation alone for controlling root-knot nematodes and other problems affecting tomatoes and peppers. Required treatment times are also shorter.

Crop Tomato and pepper fruit production

Pests Nematodes: Root-knot (*Meloidogyne* spp.)

Pathogens: Bacterial canker of tomato (*Clavibacter michiganense*)

Fusarium wilt of tomato (*Fusarium oxysporum* f. sp. *lycopersici*)

Phytophthora blight of tomato (*Phytophthora infestans*)

Phytophthora blight of pepper (*P. capsici*)

History

Horticulture is a vital and dynamic sector in Uruguay and is by far the main consumer of MB in the country. The most important products are tomatoes and peppers, although squash, string beans and eggplant are also grown, all under plastic greenhouses. Production is concentrated in the northern region of Uruguay, around the cities of Salto (730 ha) and Bella Unión (70 ha). Most of the farms are family owned operations that have been in production for many years. Except for a few instances, production is mostly destined for the local market, mainly Montevideo, the capital of Uruguay.

As of 1995 MB consumption increased, due to expansion of production areas and also to increasing losses caused by soilborne organisms. However, Uruguay made a commitment for early phase out of MB and is actively adopting alternatives.

Current commercial use

In Bella Unión, MB consumption for tomato production decreased by 80% in 2002 (in 2001 growers from this area used 5000 kg, while in 2002 it was reduced to 700 kg). They are mostly using solarisation plus metham sodium or sometimes solarisation alone. Some farmers are combining solarisation with incorporation of organic amendments, namely pepper and corn residues. In the area of Salto, solarisation plus metham sodium has been adopted by an estimated 20% of tomato and pepper growers. In many instances growers report increased yields with respect to those obtained when fumigating with MB.

Description of alternatives

Soil solarisation is based on trapping the heat from solar radiation under clear, plastic sheeting to raise the temperature of the upper 30 cm of the soil to levels of about 50ºC that are lethal to soil-borne pests. It is a cheap and simple method that promotes beneficial organisms in soil and increases soil fertility (Porter *et al.* 2001). Solarisation is suited for areas of high solar radiation, which is present for relatively long periods of time. In Uruguay, typically, a period of 28 to 30 days is needed to achieve adequate control. It has been found that when solarisation is combined with other treatments, such as biofumigation or metham sodium, efficiency can be increased and treatment times can be shortened. It also allows for the use of lower doses of metham sodium. Excellent results are obtained by these growers when using 40 cc/ m^2 of metham sodium, a 50% reduction on the traditional average dose of 80 cc/ m^2 (Bernal *et.al.* 2001).

Regulatory agency acceptance

Metham sodium has been registered in Uruguay for many years. Solarisation does not need registration or regulatory control.

Were the treatments difficult to implement?

No, but growers benefit from proper training that includes plant nutrition as biofumigation and solarisation may increase certain elements in the soil particularly nitrogen. Also, good soil preparation and moisture are important to ensure adequate efficiency of metham sodium and proper effects of solarisation and biofumigation.

Applicability to other crops and regions

Solarisation plus metham sodium can be used for other vegetable and soft fruit crops. They are cheap, efficient alternatives wherever climate, disease complexes and cropping systems permit their implementation. Wide commercial adoption has been reported in tomatoes and other vegetables in Morocco and Jordan.

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Case study 7. Use of non-chemical alternatives to MB in vegetable production in Uruguay

Biofumigation (incorporation of organic residues into the soil which produce gases that are lethal to pathogens), solarisation and resistant varieties are effective alternatives to MB used by vegetable and melon growers in Uruguay.

Crops

Tomatoes, peppers and cucurbits (melons, cucumbers)

Pests

Root knot nematodes, *Meloidogyne incongnita.*

History

In Uruguay, MB is used in protected horticulture, particularly in the production of tomatoes, peppers, cucurbits (melons and cucumbers), cut flowers and for disinfesting soil used for tobacco seedbeds and seedbeds of horticultural products. MB use is restricted to areas where intensive horticulture exists, basically the area of Salto and Artigas, in the north of Uruguay. It has not been traditionally used for strawberry production and this could well be used as an example for other regions (De León

2002). In Uruguay several non-chemical alternatives to MB have been evaluated, such as biofumigation with different types of organic waste and green manure; resistant varieties; cover crops; trap crops; and other cropping techniques, within an integrated production approach (De León 2002).

Current commercial use

In Uruguay these non-chemical alternatives are used in different crops and production zones. Their use has become a key to the control of nematodes and other pathogens in horticultural crops.

Description of Alternatives

Biofumigation. A large variety of materials have been evaluated which, when incorporated as a soil amendment may serve to control nematodes, fungi and weeds. Use of these materials is also a solution for environmental problems caused by organic residues (Bello *et. al.* 2000).

Biofumigation has been applied in Uruguay since 1996 for controlling nematodes of the genus *Meloidogyne* in different crops and production zones. Its efficacy has been confirmed in tomatoes in Tacuarembó, Montevideo and Canelones and other horticultural crops in Bella Unión, Canelones and other production areas. Different types of biofumigants have been used such as chicken manure with rice hulls, chicken, sheep or cow manure; broccoli and corn residues and agro-industrial waste, generally with similar efficacy and in some cases with better performance than that of conventional phytosanitary products (De León 2002). Biofumigation provides the additional benefit of improving soil characteristics. The methodology of application is accessible both for technical staff and for growers. Its efficacy improves when it is part of an integrated production system.

Biofumigation combined with solarisation has proved successful in many countries and can reduce the time of treatment required by solarisation alone. The plastic traps the heat from solar energy raising the soil temperature and retaining gases generated during the process. In Uruguay, different kinds of organic residues are used to perform biofumigation, among them pepper, corn and rice hulls (Bernal, pers. com. 2002).

Solarisation. In the horticultural zones of Salto and Bella Unión solarisation has been used for controlling root-knot nematodes (*Meloidogyne* spp.) with varying efficacy (Casanello and Malvarez 2001). See also Case study No. 6.

Resistant varieties. Resistant tomato varieties are being used. However, resistance may become ineffective when soil temperature rises above 27 ºC and most notably when virulent nematode populations exist. Researchers have observed that tomato varieties carrying the *Mi* gene (conferring resistance to root-knot nematodes of the species *M. arenaria, M. incognita* and *M. javanica)* are severely infected by these pathogens, frequently making production unfeasible. They consider that conventional cropping methods are contributing to the selection of virulent populations that may render the use of these resistant varieties useless in the future unless practices are changed. This is an undesirable situation since resistant varieties have been considered as a useful non-chemical alternative (MBTOC 1995).

Other cropping techniques. Mulching with organic residues has been used with the aim of regulating soil temperature. This helps to reduce the duration of nematode cycles and limits the amount of weeds. When designing integrated cropping systems it is important to consider rotation with short cycle crops like lettuce that may act as trap crops, as well as the planting time and sanitation measures that reduce risks posed by pathogens (De León 2002).

Regulatory agency acceptance

These alternatives do not require registration in Uruguay.

Were the alternatives difficult to develop?

These alternatives do not pose difficulties. They were developed through a joint research process between growers, employees, technicians and scientists.

Were the alternatives difficult to implement?

Biofumigation is easy to implement since its application is similar to that of organic amendments although the methodology is somewhat different.

Applicability to other crops and regions

Biofumigation is used in several other countries (see Case study 2). The technique can be adapted for other suitable cropping systems and regions where a large supply of organic residues is available.

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Information contributed by Leonardo de León.

Case study 8. Use of seed trays as MB alternative for tomatoes in Brazil

Seedlings are grown on trays filled with clean substrates, which are free of soil-borne pests and pathogens and do not need to be treated with MB.

Crop	Tomato seedlings	
Pests	Nematodes:	Root-knot (*Meloidogyne* spp.)
	Pathogens:	Bacterial wilt of tomato (*Ralstonia solanacearum*) *Fusarium* wilt of tomato (*Fusarium oxysporum* f. sp. *lycopersici*) *Verticillium* wilt of tomato (*Verticillium* spp.) *Fusarium* crown rot of tomato (*F. oxysporum* f. sp. *radicis-lycopersici*) Southern blight of tomato (*Sclerotium rolfsi*) *Phytophthora* blight of tomato (*Phytophthora infestans*)
	Weeds:	*Cyperus* spp. and others

History

Brazil is the largest producer of tomatoes in South America, growing nearly 3 million tonnes of fruit in 1998 (fresh and for processing). This figure has increased over the last few years and will probably continue rising. Although most of the production is for the local market, some of it is exported to neighboring countries. The tomato sector provides at least 60,000 direct jobs in Brazil and was valued at $US600 million in 1998. The industry is composed of about 10,000 growers, half of which produce in the field and the remaining half under greenhouses.

Traditionally, growers have produced tomato seedlings using the “paper-pot” method, which requires filling rolled newspaper “pots” with soil that has been previously sterilized with MB. These seedlings are then used for open field staked tomato production.

Current commercial use

Some smaller growers have adopted the seed tray method because the “paper pot” system is too time-consuming. Larger growers have adopted the system readily as it requires less labor than MB and – provided the substrate is of adequate quality – leads to very acceptable yields. Using substrates that are locally available evidently reduces costs as compared to purchased substrates (in which case costs are much higher than those of using MB).

Description of alternatives

Seedlings are grown on clean substrates, free of soil-borne pests and pathogens and which do not need to be treated with MB. Seed trays (usually 128 cells per tray) are filled with substrate and clean, pelletised seed is sown, one in each cell. Although initially commercial substrates mostly produced from composted bark and vermiculite have been used, farmers can make their own substrates at lower costs and sterilize them with solarisation or steam.

Regulatory agency acceptance

No regulatory approval is needed although some means to regulate the quality of substrates is desirable.

Were the treatments difficult to implement?

No.

Applicability to other crops and regions

Seedlings are produced in substrate trays in many countries (Canada, Denmark, Morocco, Zimbabwe, Spain) and in other crops such as vegetables, tobacco and fruit. Specifically in Argentina, substrates in trays are being introduced for the production of vegetable seedlings (A. Valeiro 2002, pers. com.).

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Case study 9. Use of ssolarisation as MB alternative for melon production in Costa Rica.

In Costa Rica, solarisation (trapping solar heat under clear polyethylene mulch) is effective and feasible in certain regions where there is sufficient sunshine and limited rainfall for an adequate period of time.

Crop Melons (fruit production)

Pests

Nematodes: Mainly root-knot (*Meloidogyne* spp.) and lesion (*Pratylenchus* spp.) but also others

Pathogens: *Fusarium* spp.

Rhizoctonia spp. *Pythium* spp. and others

Weeds: *Cyperus rotundus*

C. esculentus

Portulacca oleracea and others

History

Melons are an important crop for Costa Rica, where presently over 5500 ha are grown. A very high proportion of the production is exported bringing nearly $US50 million in 2001. The sector provides about 7000 direct jobs. Cropping is carried out between November and April for market reasons but also due to climate considerations as this period comprises the dry season.

Important soil-borne plant pathogens and pests need to be controlled to avoid substantial crop losses. For example, the reproductive capacity of *Meloidogyne* is remarkable under Costa Rican conditions: the population density can increase approximately 200 times in 30 days (Chaverri and Gadea 2001). Another important pest is nutsedge (*Cyperus* spp.), a very aggressive weed under tropical conditions. Traditionally these have been controlled with MB, which is applied in a mechanical operation at the same time as bed formation and laying of irrigation lines. Between 1995 and 1999 the sector increased MB consumption to more than 750 tonnes (Ozone Secretariat 2002), due to crop expansion, increased losses from pests and others (Hidalgo 1995), but as of 2000 consumption shows a reduction trend due to implementation of alternatives.

Current commercial use:

At present, it is estimated that about 500 ha or nearly 10% of the area grown with melons in Costa Rica is using solarisation (F. Chaverri, pers. com., 2002).

Description of alternative:

Soil solarisation occurs when heat from solar radiation is trapped under clear, plastic sheeting to raise the temperature of moist soil to levels that are lethal to soilborne pests. In general, this alternative is effective as a MB replacement under conditions of high solar radiation (sunlight) and if cropping cycles allow for a long fallow period (28 days or more). It is not suitable for all soil types and additional treatments may be required to control certain pathogens. In Costa Rica, solarisation is effective and feasible in certain western regions with non-flooding areas and where there is sufficient sunshine hours and limited rainfall during the solarisation period. It sometimes needs to be augmented with other methods of pest control.

Regulatory agency acceptance:

Solarisation does not require registration or regulatory control in Costa Rica.

Were the treatments difficult to implement?

No.

Applicability to other crops and regions

Solarisation is a proven alternative to MB in many countries around the world where climate, disease complexes and cropping systems are suitable for its implementation (Katan 1996, Katan and DeVay 1991, Elmore *et al.* 1997). There is wide commercial adoption of this technique for example in Jordan and Israel by growers of tomatoes and other vegetables (V. Hasse, pers. com., 2002). Excellent potential for commercial adoption is reported in Morocco for melon growers (Case study 10). Tomato growers in Uruguay are successfully adopting solarisation plus metham sodium or biofumigation (Case study 6).

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Case study 10. Use of solarisation as an alternative to MB for the control of broomrape (*Orobanche ramosa*) in melon under plastic tunnel conditions in Morocco.

Melon rows are mulched with clear polyethylene, in order to trap solar heat in the soil. Temperatures achieved are lethal to a noxious parasitic plant called broomrape.

Crop

Melon

Pests

Orobanche ramosa, a parasitic plant commonly known as broomrape

History

In some Moroccan regions, all vegetables grown in plastic tunnels are attacked and severely damaged by a broomrape, *Orobanche ramosa*. MB is widely used to control this parasite as well as other soilborne pathogens, insects and weeds. Other alternatives such as resistant varieties, grafting, cultural practices and particularly crop rotation do not provide sufficient control of broomrape. The lack of resistant varieties and the prolonged seed viability of *O. ramosa* (up to 20 years) are the main factors rendering control of this parasitic plant difficult. Furthermore, seed germination is stimulated by host root exudates and even a few seeds may cause large broomrape outbreaks.

Current commercial use

No wide scale adoption yet, but with MB phase-out, use of this alternative should increase in the future.

Description of Alternative

To provide solarisation conditions, melon rows are mulched with polyethylene (100µ thick) in June. This same polyethylene is kept in place and acts as a regular mulch after planting. The soil is kept moist so as to increase the thermal sensitivity of the seeds and improve heat conductivity. Plastic tunnels are irrigated 2 days before setting up the mulch and after that every week by drip irrigation, during the entire solarisation period (35 days).

Solar heating of the soil by this system efficiently controls broomrape, in heavily infested soils to levels comparable to those achieved with MB. Furthermore, soil solarisation is better than fumigation as it is cheaper and safer, does not leave chemical residues, carries no risk of phytotoxicity and does not require sophisticated equipment. Mulching can be easily set up by hand inside the plastic greenhouses. The drip irrigation system and the plastic used for solarisation remain useful for the entire production cycle. Therefore, control of *Orobanche* by soil solarisation does not require additional investments.

Regulatory agency acceptance

Solarisation does not require registration in Morocco.

Were the treatments difficult to develop?

It was necessary to adapt the solarisation technique to the plastic tunnel production system. It is important to note that in order to achieve adequate control of some other pests such as nematodes, solarisation must be part of an IPM programme for managing soilborne pests.

Were the treatments difficult to implement?

No.

Applicability to other crops and regions

Yes, on other vegetables such as cucumber, squash and tomato.

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Information contributed by Prof. Mohamed Besri

Case study 11. Use of solarisation and IPM for tomatoes and peppers in Florida and Southeastern USA .

The incorporation of certain methods of strip solarisation into the standard raised-bed plastic mulch tomato/pepper production system has been found to provide adequate levels of pest control.

Crop	Fresh Market Tomatoes and Peppers	
Target Pests	Nematodes:	Root-knot (*Meloidogyne* spp.) Reniform (*Rotylenchulus reniformis*)
	Pathogens:	*Fusarium* wilt of tomato (*Fusarium oxysporum* f. sp. *lycopersici*, races 1, 2 and 3) *Fusarium* crown rot of tomato (*F. oxysporum* f. sp. *radicis-lycopersici*) Southern blight of pepper and tomato (*Sclerotium rolfsi*) *Pythium* root rot of pepper (*Pythium myriotilum* and *P. aphanidermatum*)
	Weeds:	Purple nutsedge (*Cyperus rotundus*) Yellow nutsedge (*C. esculentus*) Purslane (*Portulaca oleracea*)

History

MB has been an important component of horticultural production systems used in the southeastern US for thirty years. Florida state is the largest producer of fresh market tomato and pepper in the United States, growing 17,520 and 7,440 ha of tomato and pepper, respectively, in 2000/01. The development of alternatives was started in the 1990s in response to the Montreal Protocol controls on MB. Initial trials using broadcast soil solarisation were marginally effective in controlling key soilborne pests of tomato and providing yields equivalent to MB fumigation (Overman 1985, McSorley and Parrado 1986). The effectiveness of soil solarisation was improved when it was integrated into the production system by solarising the raised, plastic mulched beds (Chellemi *et al*. 1997c).

Current commercial use

Solarisation is beginning to be adopted on large commercial farms (Winsberg *et al*. 1998).

Description of alternatives

Incorporating strip solarisation into the standard raised-bed plastic mulch tomato/pepper production system can produce yields similar to that produced with MB (Chellemi *et al*. 1997abc). Strip solarisation presents no added expense as plastic mulches are part of normal production. Following the solarisation period, the clear plastic is painted with a white water-based latex paint. The white plastic then serves as a production mulch for the subsequent crop. The cost of the paint is approximately $US135 per hectare (Chellemi *et al*. 1997c). Since many growers prefer to prepare a proportion of their beds in advance, the extra time period required is not a limiting factor.

Soil solarisation was shown to be cost-effective, compatible with other pest management tactics, readily integrated into standard production systems and a valid alternative to pre-plant fumigation with MB. It provided equivalent control of nutsedge species in Florida and Georgia (Chellemi *et al*. 1997c, Chase *et al*. 1999a, Gilreath *et al*. 2001). Control was attributed to a combination of the photomorphogenic effect of translucent film and the scorching of shoots emerging underneath the plastic (Chase *et al*. 1998, 1999b; Patterson 1998). Three consecutive years of soil solarisation in a field heavily infested with nutsedge species did not result in a loss of efficacy and no evidence of nutsedge emerging from areas outside the solarisation zone was noted (Gilreath *et al*. 2001). Soil solarisation did not control rootknot nematode population (Chellemi *et al*. 1997abc, Gilreath *et al*. 2001). However, when solarisation was combined with a low rate of 1,3-dichloropropene and chloropicrin (16.2 and 3.4 g m^{-2}, respectively) effective control of rootknot nematode was obtained (Chellemi *et al*. 1997ac). The combination of soil solarisation and *Gliocladium virens* provided control of southern blight caused by *Sclerotium rolfsii* on pepper and tomato in North Carolina (Ristaino *et al*. 1991, Ristaino *et al*. 1996).

The technical feasibility of soil solarisation was validated in 21 large scale demonstration trials conducted in commercial farms (Chellemi *et al*. 1997abc, Chellemi 2001). The minimum size for treated areas was 0.2 ha. Tomato yields obtained with solarisation ranged from 85- 106% of those found with MB while the average yield was 95%. Yields of pepper obtained with solarisation ranged from 93-106% of those with MB and the average yield was 98%. Several weed species were not controlled including purslane (*Portulaca oleracea*) and Texas panicum (*Panicum texanum*). Painting of the plastic at the termination of the solarisation period was found to be a critical procedure to avoid yield losses caused by heat stress to transplants.

Regulatory agency acceptance

Solarisation does not require registration in USA.

Were the treatments difficult to develop?

Development of solarisation was a little difficult because it had to be adapted to the present production system. The most difficult problem is the transition from a single tactic approach to an IPM approach for management of soil-borne pests.

Were the treatments difficult to implement?

No. Soil solarisation of tomato/pepper crops in Florida is limited to autumn production systems, as solar radiation in winter is not sufficient to provide the soil temperature required for successful solarisation. This limits use of this method to 50% of Florida's production acreage. Rainfall can reduce the efficacy of solarisation and is therefore best suited to periods of high temperature and limited rainfall for an adequate period of time (see Case study 9).

Applicability to other crops and regions

Studies on strawberries, cucumbers and watermelons are under way in Florida. An agricultural extension booklet published by the University of California lists the species of nematodes, fungi, bacteria and weeds that are known to be controlled adequately by solarisation in California (Elmore *et al.* 1997).

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Case study 12. Use of substrates for greenhouse strawberries in UK.

Substrates are frequently used for greenhouse crops in the UK, and there is also some use in open fields. Since they are disease and pest free, there is no need for sterilisation by fumigation.

Crop

Greenhouse and open-field strawberries

Target pests

Nematodes: *Meloidogyne hapla*
Longidorus elongates
Pratylenchus penetrans
Pathogens: *Phytophthora fragariae* (red core), *P. cactorum* (root rot)
Verticillium spp. (wilt)
Weevils: *Otiorhyncus ovatus* (vine weevil)
Weeds: All kinds, particularly thistle

History

Strawberry production in the UK is an economically significant sector, even in the cooler regions. Scotland, for example, produced about $US20 million worth of strawberries in 1998, on a production area of about 4,000 ha. The strawberry industry provides about 400 permanent jobs and 20,000 temporary jobs in that region alone. Strawberry enterprises range in size from 2 ha to more than 40 ha.

The UK used an estimated 350 tonnes MB for strawberries in 1993, and about 100 tonnes in 2000.

Commercial use

Substrates are now widely used for greenhouse production in the UK, and used to a small extent in open fields (P. van Luijk, pers. com, 2002). Scottish growers, for example, first started using substrates in 1988, when they received technical support from organisations such as the Agricultural Development and Advisory Service (ADAS) and the Farm Advisory Service Team (FAST), together with the Agricultural Extension Service and consultants from The Netherlands.

Description of alternatives

Substrates are disease and pest free, so there is no need of sterilisation by fumigation. The substrates most commonly used are black and white peat imported from the Netherlands and Ireland. More recently growers have mixed this with coconut fibre imported from Asia.

Each pot or bag filled with substrate is separate, so pathogen spread is very much restricted. The substrate can be used twice for strawberry production and afterwards sold to garden centres or used as a soil amendment in other parts of the farm.

Yields are typically 20% higher than when growing on MB treated soil, since growers can optimise fertiliser and water management. Further, substrate growing allows for two crops per year. These two factors together make it possible to pay off higher costs involved in substrate production as compared to fumigating with MB (Nuyten 2000).

Regulatory agency acceptance

No regulatory approval required. The reduced use of pesticides makes strawberry fruit more acceptable to supermarkets. Peat supply may be an ecological problem, so growers are increasingly adopting coco fibre and other substrates.

Were the treatments difficult to implement?

No, but good technical advice, water and soil analyses and management as well as good quality plant material are needed to ensure success of the system.

Applicability to other crops and regions

Substrate systems for strawberries were first developed in The Netherlands in 1975 and have since been widely adopted and adapted in other countries (Nuyten 2000, FAO 1990; López-Medina 2002). A number of agricultural extension handbooks on substrates are available (e.g. Benoit 1992, DLV 2000, FAO 1990, FAO and UNDP 1990, Kipp *et al.* 2000, MAFF 1994). Since substrate systems do not rely on climatic conditions or soil types, they can be used anywhere in the world where suitable substrate materials are available. They can also be used for a wide range of horticultural crops such as tobacco seedlings, flowers, pepper, tomato, cucumber and eggplant (UNEP 2001).

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Case study 13. Use of substrates as MB alternative for strawberry production in the Netherlands and Germany.

A large proportion of strawberry production in greenhouses is carried out on substrates (peat or coconut fibre) in plastic bags or other containers.

Crop	Strawberries.	
Pests	Nematodes:	*Pratylenchus penetrans* *Meloidogyne hapla*
	Pathogens:	*Verticillium albo-atrum* *V. dahliae* *Phytophthora cactorum* *P. fragariae*

History

In the 1970s and early 1980s, Dutch horticulture depended heavily on MB, using around 3,000 tonnes. Environmental concerns about MB led the Dutch government to establish a phased withdrawal of MB. Soil fumigation with MB was used for strawberry production from the 1960s until it was banned in 1992. In Germany, the use of MB declined because of strict environmental controls on pesticide use, resulting from concerns about pesticide residues in food and ground-water. As a result of these changes, production systems using substrates were developed.

Current commercial use

Virtually 100% of the greenhouse strawberry production in the Netherlands uses substrates. There are approximately 2000 ha of greenhouse and field strawberries grown in the Netherlands. In 1993, 30,000 tonnes of strawberries were produced, of which 15,000 tonnes were from greenhouses using peat bag substrates (de Barro 1995). Greenhouse strawberry producers in Germany also adopted similar substrate systems.

Description of alternatives

The substrates are pathogen-free materials, generally peat and/or coconut fibre/coir contained in plastic bags, buckets and other types of containers. Water and nutrients are supplied by drip irrigation. This system is used in glasshouses and plastic tunnels, and is sometimes used for open field production. The Dutch systems often require a high investment. However, cheaper, simpler systems are also in use.

Strawberry fruit yields from substrate systems greatly exceed the yields obtained with MB. They also allow early production when prices are higher.

Regulatory agency acceptance

Not required.

Was the alternative difficult to develop?

Yes. The substrate technology was developed from the early 1980s and numerous problems had to be overcome.

Was the treatment difficult to implement?

No. Adequate government support for technology transfer was provided in the Netherlands. The increase in farmer's income was a decisive stimulus.

Applicability to other crops and regions

Substrates are used for the production of many kinds of vegetables, fruit and ornamental crops. In the Netherlands, a total of 6,530 ha used substrates in 2000 (Miller 2001). Use of substrates is increasing in all regions of the world, including Article 5(1) countries. While strawberry producers use primarily peat and coconut fibre/coir, a diversity of substrate materials are used in other crops such as tomatoes and cut flowers (UNEP 2001).

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Case study 14. Use of substrate systems as MB alternatives in tomato and pepper production in Hungary

The production of crops in clean, disease-free substrates, makes soil disinfection unnecessary. Substrate materials can include peat, coconut waste, composted pine bark, mature compost, small stones, as well as other substances or mixtures.

Crop

Tomato and peppers produced in greenhouses and plastic tunnels

Target pests

Nematodes: *Meloidogyne* spp. (*M. hapla, M. incognita, M. arenaria, M. javanica, M. thameesi*)

Pathogens: *Pyrenochaeta lycopersici*, *Sclerotinia* spp, *Fusarium* spp. and others

Weeds: Many kinds

Other pests: Noctuidae (Lepidoptera), Gryllotalpidae (Saltatoria) and others.

History

Vegetable production is a very important part of Hungarian horticulture. The total area of greenhouses and plastic tunnels is about 5,400 ha, including about 2,250 ha of pepper and about 1,200 ha of tomato. A narrow range of crops has been grown on the same area for many years, leading to severe nematode and disease problems. As a result, a large vegetable producer in Hungary, Árpád-Agrár Co, introduced MB soil disinfestation in the 1980s. More than 500 farming families produce vegetables for Árpád in more than 86 ha of glasshouses and plastic tunnels. After becoming aware of the Montreal Protocol's MB phase-out requirements, the company trialled tomato production on rockwool slabs in 1998.

Commercial use

Árpád obtained good results with rockwool substrates, and by 2002 had introduced substrate production on a total of 11 ha, comprising 8 ha pepper, 2 ha tomato and 1 ha cucumber. As a result of their successful experience, the company aims to convert all their glasshouses to rockwool by about 2005 (Kovács 2002a).

For many smaller farms and plastic tunnels, rockwool slabs are not appropriate, so simpler substrate systems have been introduced as well. By 2002, for example, 50-60 small family farms were producing crops on cheaper substrates (e.g. volcanic limestone) on about 15-20 ha in total. They produce mainly tomato, but also melon and cucumber.

Description of alternatives

The production of crops in clean, disease-free substrates, makes soil disinfection unnecessary. Substrate materials can include peat, coconut waste, composted pine bark, mature compost, small stones, and many other substances. They are often made from mixtures of materials, to support the correct movement of water, nutrients and air for each.

crop and provide adequate anchorage for plants. The resulting vegetables tend to be more uniform and of higher commercial quality grade than crops grown using traditional methods.

Rockwool slabs: The larger glasshouses were substantially upgraded before installing Dutch-style rockwool systems. Broken panes were repaired, insulation was renovated, and heating, irrigation systems and computer-controlled equipment was installed. The crops are grown in slabs of rockwool laid on plastic sheets. Rockwool provides tomato yields of about 40 kg/m, compared to only about 22 kg/m when using MB. Rockwool systems require a high initial investment, but the substrate system is much more productive than the MB system, so the investment cost is recovered in 4 - 5 years (Kovaks 2002a).

Substrates in containers: On the small farms, peat and/or perlite substrate is placed in 10 litre pots, and two tomato plants are planted per pot. The pots are placed in rows on plastic sheets on the floors of greenhouses and tunnels. The sheet prevents pests entering pots from the soil below. Drip irrigation lines are placed along the top of the pots to provide water and nutrients. After the crop is finished, the substrate material can be used again in forestry nurseries. The substrates provide higher yields of tomatoes and peppers than conventional production using MB in these conditions. Tomato yield is 15 kg/m compared to only 10 kg/m using MB (Kovács 2002b). This substrate system requires substantially less investment than rockwool, costing only slightly more than MB. However, the substrate system is more profitable than MB.

Grafted plants + IPM: Some plastic tunnels use pepper varieties grafted onto resistant rootstock, combined with the use of selected chemicals or IPM. This gives pepper yields of about 16.5 kg/m compared to about 12-13 kg/m using MB (Kovács 2002b). The grafting is economically viable because the rootstock allows sufficient uptake of nutrients and water to support fruit production on two stems instead of one.

Regulatory agency acceptance

Substrate systems and grafted plants do not require registration from the authorities responsible for pest control products in Hungary.

Were the treatments difficult to implement?

No.

Applicability to other crops and regions

Substrates are used in all climates from tropical to arctic. They are used for the production of a very wide range of fruit, vegetables, salad crops and herbs in countries such as Australia, Belgium, Canada, Denmark, Finland, France, Hungary, Netherlands, New Zealand, Poland, South Africa and Turkey (UNEP 2001).

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Case study 15. Tomatoes in New Zealand: Substrates and *Trichoderma.*

Tomato plants are grown in a sawdust substrate derived from pine trees, which is a waste product from the timber industry. Trichoderma is added regularly through the irrigation system.

Crop

Greenhouse tomatoes

Target pests

Nematodes: *Meloidogyne* spp.
Pathogens: *Fusarium* spp., *Pythium* spp., *Phytophthora* spp.
Pythium myriotilum and *P. aphanidermatum*
Weeds: Various species

History

New Zealand produced about 29,796 tonnes of tomatoes during the 1997/98 season with a market value of about $US48 million. Production has been steadily increasing over the last decade. Most of the production is for the local market although there are some exports mainly to Australia and the Pacific Islands. There are nearly 600 growers. Tomatoes to be used fresh are usually grown under greenhouses, while fruit that is to be processed is grown in the field.

MB was widely used for greenhouse tomatoes in the past but less that 5% of the growers presently use it since most have adopted alternative systems. This case study refers to experiences at GDW Gargiulo and Sons, a 4 ha greenhouse facility containing 55,000 tomato plants.

Commercial use

Many growers in New Zealand are using sawdust as a substrate for greenhouse tomatoes, since it offers improvements in crop management as compared to fruit produced in ground beds. It is estimated that at present, about 95% of the greenhouse crop grown in this country is using sawdust or other soil-less substrate. Addition of *Trichoderma* as a beneficial treatment is also increasing.

Description of alternatives

Gargiulo and Sons use a combination of sawdust substrate derived from pine trees, which is a waste product from the timber industry. They add *Trichoderma* regularly through the irrigation system. *Trichoderma* is a fungus that helps control or suppress certain pathogenic fungi such as *Pythium, Fusarium* and *Rhizoctonia*. The substrate is placed in black plastic bags which are newly filled each year. Two plants are planted per bag. Water use, electrical conductivity and nutrient levels are monitored regularly.

The system provides highly effective prevention of diseases and the addition of *Trichoderma* is truly beneficial as it not only increases root rot control but it also improves the root system. A 10% increase in yield has been reported.

Regulatory agency acceptance

Substrates do not need registration. The *Trichoderma* formulation is sold as a soil/ media bioinoculant without specific disease claims and as such does not require registration in New Zealand or Australia. This system is acceptable for use by certified organic producers.

Were the treatments difficult to implement?

No. Setting up the substrate bags probably requires more labour than MB fumigation but the system is still cost effective. Growers need to be able to monitor plant water and nutrient relations.

Applicability to other crops and regions

The substrate + *Trichoderma* system is used in many countries besides New Zealand, e.g. Australia, Denmark, South Africa and Turkey, and also on other crops besides tomatoes such as cucurbits, peppers and flowers (Hunt 2000).

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Case study 16. Use of substrates for greenhouse and open field tomato production in Belgium.

Tomatoes are grown in rockwool slabs under greenhouses. Some summer production also takes place in buckets filled with coconut coir and placed on plastic-covered soil out in the fields.

Crop

Tomato (greenhouse and field crops)

Target pests

Nematodes:*Meloidogyne* spp.

Pathogens:*Pyrenochaeta lycopersici* (corky root of tomato)

Fusarium spp.

Rhizoctonia spp.

History

Horticulture in Belgium is an active and rapidly developing sector; tomatoes are the most important crop from a financial point of view.

For over 40 years Belgian growers have relied on soil sterilisation to eliminate “accumulated microbiological soil sickness”, a result of continuous monoculture or insufficient crop rotation. Soil sterilisation has been almost exclusively achieved with soil fumigants such as MB, chloropicrin, 1,3-dichloropropene, dazomet and metham sodium. Steam is used in some instances but is relatively expensive.

Over the last decade MB consumption has been decreasing steadily. In 2000 only one third of the amount used in 1991 was consumed. In 2001 the reduction went further and amounted to only about 10% of the 2001 figure. The decrease, particularly in the tomato sector is due to better quality and yields obtained with soilless culture, and also to restrictions on pesticide residues (including MB) and consumer concerns. Use of MB is excluded in the guidelines for production of food that is marketed as ‘organic’.

Commercial use

Approximately 75 – 80% of the tomatoes and 100% of the cucumbers and sweet peppers are produced in rockwool substrate, with no need for soil fumigation (Pauwels 2002). Some production in coconut coir has also been introduced.

Description of alternatives

Tomatoes are grown in rockwool slabs in greenhouses. Some growers also carry out summer production in buckets filled with coconut coir and placed on plastic-covered soil out in the fields. Pest and disease problems that can still attack plants grown in substrates can be avoided by replacing the old substrate or by sterilizing it with negative pressure steaming. Addition of beneficial microorganisms (antagonists) brings positive results, helping to control these problems (Pauwels 2002).

Regulatory agency acceptance

Substrates do not need registration in Belgium.

Were the treatments difficult to implement?

No, but growers need to monitor water and nutrient relations more closely. It is crucially important to make early and correct diagnosis of diseases and pests.

Applicability to other crops and regions

Since their development in countries like the Netherlands and Israel, production in substrates has become a significant commercial trend in many regions and for many crops, particularly intensive production systems such as for vegetables, tobacco and cut flowers (refer to references in Case study 12).

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9.3 Case studies on alternatives to MB for soil uses - ornamentals and tobacco.

- CS 17. Use of floating trays as MB alternative for tobacco in Argentina
- CS 18. Use of floating trays and other non-chemical methods for tobacco seedlings in Cuba
- CS 19. Use of IPM strategies for control of *Sclerotium* rot in the Australian flower bulb industry

CS 20. Use of steam soil pasteurization for controlling Fusarium wilt of carnations in Colombia

CS 21. Use of substrates as an alternative to avoid the use of fumigants in carnation and rose production in Colombia

Case study 17. Use of floating trays as MB alternatives for tobacco seedlings in Argentina

Production of tobacco seedlings in floating trays avoids the need for fumigating with MB. Although the capital cost is presently more expensive, the system will be cost effective once trays and substrates can be sourced locally.

Crop

Tobacco seedlings

Pests

Weeds (*Amaranthus* spp., *Cynodon* spp., *Cuscuta* spp., *Portulacca* spp. and others). Fungi (*Fusarium* spp., *Pythium* spp.), nematodes (*Meloidogyne* spp,), soil insects.

History

Argentina has a long history of tobacco production, and the crop has substantial economic importance; the domestic market for cigarettes is worth more than $US 2,421 million, while cigarette exports are worth about $US190 million. Tobacco is grown on about 79,000 ha in seven Argentine regions. There are about 24,400 tobacco producers, 80% of whom are small scale farmers.

MB has been used for many years in farms of all sizes, providing good control of soil pests and diseases that commonly attack tobacco seedbeds. MB consumption was more than 268 tonnes in Argentine tobacco seedbeds in 2000.

Current commercial use

National trials started in 1998/9 as part of a UNDP demonstration project, establishing the float system successfully on a number of peasant farms. Float trays were also installed by several large tobacco producers. The capital cost for the floating tray system prevented further adoption initially, but Argentina is now implementing a MLF MB phase-out project, which will overcome the economic barriers by providing tobacco farmers (particularly small scale farmers) with training and materials/equipment for establishing the floating tray system, so that MB can be eliminated throughout Argentina. In 2002, the first year of the project, more than 2,760 farmers were trained how to use alternative techniques (A. Valeiro, 2002, pers. com.).

Description of alternative

In the floating seed-tray technique the need for soil sterilisation is avoided by using disease-free substrates. In Argentina, the substrate introduced initially is a mixture of peat and perlite or vermiculite, which is imported from abroad.

To set up the system it is necessary to build a shallow pool on levelled ground. A low wall of brick or wood (12 cm high) is erected around the bed and the whole bed is covered with thick black polyethylene. The pool is filled with clean water. Tobacco seedlings are planted in substrate in polystyrene trays of about 288 cells each, which are then floated in the shallow pool. Fertilisers or algicides may be added to the water if needed.

The harvested tobacco leaves are more uniform and of higher quality grade, giving a better end product compared to seedlings produced with MB fumigation. Furthermore, less land is required for seedling production

Regulatory agency acceptance

No regulatory approval is required in Argentina.

Were the treatments difficult to develop?

No, there is presently ample experience with this system which has been used for some time in countries such as the United States, Cuba and Brazil.

Were the treatments difficult to implement?

No, however training and technical assistance is required. Adequate supply of materials (trays, substrates) is also needed.

Applicability to other crops and regions

This alternative has been very successful in other countries like Brazil, where it has been adopted by about 60% of the production area in Rio Grande do Sul, where much of the country's tobacco production takes place (Salles 2001). The system is being adapted to different areas and climatic zones. In Argentina, the system has been adapted for tomato and pepper seedlings with remarkably good results (A. Valeiro pers. com. 2002).

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Case study 18. Use of floating trays and other non-chemical methods for tobacco seedling production in Cuba

Tobacco seedlings are produced in trays filled with pathogen-free substrate. A mixture of local peat, roasted rice bran and zeolite has been used successfully. Addition of Trichoderma, a fungal biocontrol agent has also proven beneficial.

Crop Tobacco seedlings

Pests

Nematodes: Mostly rootknot (*Meloidogyne incognita*)

Pathogens: *Phythopthora parasitica*.
Rhizoctonia spp.
Pythium spp.
Peronospora tabacina

Weeds: *Cyperus* spp *Portulacca* spp. *Amaranthus* spp. *Sorghum halepense* and others

Insects: *Heteroderes laurentii, Grillotalpa hexadactila, Feltia* spp.

History

Tobacco is an important and traditional product for Cuba, enjoying excellent reputation around the world. Growers are located in diverse regions all over the country and about 40,000 farmers associated in cooperatives depend on this crop for their livelihood. Over 50,000 ha are presently under production.

In the 1980s Cuba used about 400 tonnes MB for several crops, primarily for sterilizing tobacco seedbeds to control soil pests, diseases and weeds (UNIDO, 2002). This was reduced first by the introduction of an IPM alternative system designed for tobacco seedbeds, and later by the widespread introduction of the floating tray system. In 1998 only 80 tonnes of MB were consumed, and this has been further reduced recently.

Current commercial use

The Plant Health Institute and the Research Institute for Tobacco of Cuba have played a key role in transferring the floating tray technology to growers. By early 2002, a MB phaseout project in Cuba had erected 1264 micro-tunnels for small farmers with a total area of 41,780 m^2 and 52 new greenhouses on a total area of 48,468 m^2 so that groups of farmers could use the floating tray method (E. Pérez, 2002, pers. com.). Through extension work, nearly 2000 farmers had received training and by early 2002 they had adopted the system (Pérez *et al.* 2002). The institutes mentioned above have also been instrumental in providing IPM training to farmers over the last twenty years, which increases the success rate of this technology (Fernández *et al.* 2002b).

Description of alternative

In this system, seedlings are produced in trays filled with certified substrate free of pathogens. Typically, 264-cell polystyrene trays with 17 cc/cell are used. Trays are then placed in a shallow pool lined with black polyethylene and filled with water, to which fertilizers and algicides may be added if necessary. Many types of substrates can be used (e.g. peat, vermiculite, coconut coir, composted bark etc.). In Cuba, a mixture of local peat, roasted rice bran and zeolite, all of which are produced locally, have been used successfully. Addition of *Trichoderma*, a fungal biocontrol agent, has also proven beneficial (Fernández *et al.* 2002b).

With the floating tray system seedlings are more uniform and of better quality, since pests and diseases are controlled more efficiently, germination rates are better and nutrition is closely monitored. Transplant success rates are also higher.

Regulatory agency acceptance

This system does not require registration.

Were the treatments difficult to implement?

No, but growers need to learn good water and nutrient plant relations. Further, identification of locally available, inexpensive substrates is important for making costs acceptable. Commercial production of the substrate material requires quality control procedures to ensure that the substrate products are disease-free and have the correct composition for successful plant growth.

Applicability to other crops and regions

Floating trays are widely used by many tobacco producing countries around the world. Successful and wide commercial adoption has been reported in Article 5(1) countries for example in Zimbabwe, Brazil and Argentina (A. Sabater, pers. com. 2002; case study No. 17). It is also used in non-Article 5(1) countries such as Spain, France, Italy and the USA

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Case study 19. Use of IPM strategies for control of *Sclerotium* rot in the Australian flower bulb industry

The IPM programme relies on use of clean planting material, monitoring of the pathogen in soil, minimal cultivation and strategic use of fungicides. Yields are equivalent to those obtained with MB.

Crop Flower bulbs: Dutch Iris, Lilliums, Amaryllis.

Pathogen *Sclerotium rolfsii.*

History

In 1992, *Sclerotium* rot, *Sclerotium rolfsii*, was the major disease problem in the SE Australian flower bulb industry. This region produces about two thirds of Australia's bulb production. Losses due to this disease were estimated at $A5 million.

This industry has been solely dependent on fumigation with MB/chloropicrin mixtures 98:2 (100 g m^{-2}) and 70:30 (50g m^{-2}) in open fields and protected crops for over 20 years. Soil disinfestation was used mainly for control of *Sclerotium* rot and also for weed control and the uniform growth obtained after fumigation.

Current commercial use

Currently, 100% of growers have adopted some components of the IPM programme.

Description of the alternative

The programme relies on use of clean planting material, monitoring of the pathogen in soil, minimal cultivation and strategic use of fungicides (tolclofos methyl, tebuconazole). It has successfully achieved healthy bulb yields equivalent to those obtained with MB and reduced disease incidence from 80% to less than 5%.

Comparatively, the IPM programme was more economical than MB use (see Table CS19.1 below). However, farmers still needed soil disinfestation to eradicate the fungus from soil. For this reason a combination of IPM and fumigation is used. Clean planting stock also enabled fumigation to be 99% effective.

Regulatory agency acceptance

Full implementation is being hampered by lack of registration of two of the fungicides because of minor use registration problems, i.e. the market size is considered too small.

Was the system difficult to develop?

Four years of research were necessary to identify all factors contributing to disease development and to develop cost effective, strategic application methods for fungicides which were not phytotoxic.

Was the system difficult to implement?

No. Bulb dipping facilities already existed in the industry. Currently they are importing disease-free bulbs from the Netherlands

Applicability to other crops and regions

The treatment was developed for Dutch Iris, but could be used on 11 crops in the bulb industry.

Table CS19.1 Comparative costs ($A) of Dutch Iris produced using an IPM strategy or with soil treated with pre-plant applications of methyl bromide/chloropicrin (70:30).

	Methyl bromide $ / ha	IPM $ / ha
Fumigation	6,500	Nil
Plastic removal and disposal	100	Nil
Soil sampling and sclerote extractions	Nil	300
Bulb dips, pre-sowing	Nil	200
Other fungicides	2,500	2,500

Herbicides	900	900
Hand weeding	600	600
Extra Herbicides	Nil	160 x 2 = 320
Extra hand weeding	Nil	600
Total costs	10,600	5,420

Note:In general, costs which are identical to both programmes have not been included, e.g. planting, pre-storage dips. Australian labour costs have been calculated @ AUS$17.50 /hour. Data, obtained for 1998, is still considered valid

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Case study 20. Use of steam soil pasteurisation for controlling Fusarium wilt of carnations in Colombia

Sterilisation of the soil with steam reduces the pathogen population significantly in the first 30 cm of soil, at costs that are comparable to those of MB and other fumigants.

Crop Carnation cut flowers

Pests Pathogens: *Fusarium* wilt of carnations (*Fusarium oxysporum* f. sp. *dianthi)*

History

Carnations are an important crop within the Colombian flower sector, accounting for about 35% of total flower exports, which were valued at $US600 million last year. Colombia is the second-largest world flower exporter after the Netherlands and the sector provides more than 70,000 direct jobs plus many more indirect ones.

Fusarium wilt of carnations is the most serious disease affecting this flower. It may limit production to such an extent that it simply puts a grower out of business or forces them to look for new, uninfested land on which to grow carnations. The causal agent is soilborne and once the disease is well established it is difficult and costly to eradicate. Traditionally, steam and soil fumigants have been the treatments of choice for this disease.

Current commercial use

Steam has been used by large carnation growers in Colombia for many years. It is also used by flower producers in the Netherlands, France and Italy, and is being introduced in countries such as Zimbabwe, Costa Rica and Kenya.

Description of alternative

In very simple terms, steam sterilization involves injecting or otherwise diffusing hot water vapour into the soil with the aid of a boiler and conductors such as metal or hose pipes in order to kill noxious soilborne organisms. Soil temperature and treatment duration determine whether complete elimination (sterilisation) or only partial removal of soil microflora (pasteurisation) occurs. Because very high temperatures are difficult to maintain and may lead to phytotoxicity problems, pasteurisation is usually preferred. As a general rule, it is recommended to carry out treatment so that the coldest spot in the soil or substrate is held at 70°C for ½ hr. Depending on the system used, the soil may need to be covered with canvas or an insulated plastic sheet to keep the steam in contact with it.

The method used in Colombia reduces the pathogen population significantly in the first 30 cm of soil, at costs that are comparable to those of fumigants, including MB (Carulla 2002, Pizano 2001,2002). Resistant varieties work well with steam, as they can be grown in areas where disease has occurred in the past. Steam has other benefits when compared to fumigants, for example not requiring a waiting period before replanting, which may add an entire month of flower production (or about 215,000 exportable carnation flowers) to steamed areas (Pizano 2001).

Regulatory agency acceptance

Steaming itself is not subject to regulatory control as a pest control method in Colombia. However, worker protection standards need to be observed when operating the boilers.

Were the treatments difficult to implement?

Many variables influence the success and cost effectiveness of steam, for example the boiler and diffusers used, soil type and structure and soil preparation. Steam must be used as part of an integrated management system that helps maintain diseases and pests at a low level of incidence and avoid recontamination.

Applicability to other crops and regions

Steam sterilisation is a form of physical control that has been found suitable as an alternative to MB for intensive growing systems such as cut flowers, particularly in developing countries where labour is more readily available at reasonable costs. Negative pressure steaming, which distributes steam more evenly in the soil, and reaches greater depths, is used in the Netherlands and is now being adopted in some Article 5(1) countries in MB phase-out projects (M. Barel, pers. com. 2002).

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Case study 21. Use of substrates as an alternative to avoid the use of fumigants in carnation and rose production in Colombia

Adaptation of techniques and locally available substrates have made soilless cultivation economically feasible in many countries. Fumigation is not needed.

Crops

Carnations, roses

Pests

Fusarium wilt of carnation -*Fusarium oxysporum* f.sp. *dianthi*
Symphyllans - *Scutigerella* spp.
Collembolans - *Onychiurus* spp.
Nematodes - *Meloidogyne* spp.
Pratylenchus spp.

History

Carnations and roses are the most important floral products of Colombia, accounting for approximately 60% of total flower exports. Presently, there are about 5,900 Ha grown with flowers in Colombia for export purposes; the sector brought over $US600 million in revenues to the country last year and is a very important employment provider.

Fusarium wilt of carnations is the most serious disease affecting carnations. It may limit production to such extent that it simply puts a grower out of business or forces him to look for new, uninfested land on which to grow carnations. The causal agent is soilborne and once the disease is well established it is difficult and costly to eradicate. Traditionally, steam and soil fumigants have been the treatments of choice for this disease. A similar situation arises with respect to roses in areas that have become seriously infested with root-knot nematodes. Soil arthropods (collembolans, symphyllans) also cause problems, particularly in soils where roses or carnations have been grown repeatedly for many years.

Current commercial use

About 40% of the carnation growers have shifted from growing in the natural soil to growing in substrates. It is estimated that about 25% of the total flower industry in Colombia has shifted to hydroponic production systems.

Description of Alternative

In recent years, carnation growers, looking for alternatives to control fusarium wilt in Colombia, have successfully developed a system that offers the advantages of artificial substrates placed above ground but without the high costs associated with construction of raised beds and necessary infrastructure. In this system, "beds" are made out of heavy polyethylene film laid directly on the ground; this material provides isolation from the soil. The beds are then filled with partially burnt rice hulls to a depth of 15 to 20 cm. The substrate is burnt to eliminate possible pests or pathogens and improve texture. Burning is easily achieved by simply setting fire to dry rice hull piles and then sprinkling water to kill off the flames. Carnation plants are then grown in these beds following the usual cultural practices. Growers are continuing to further improve the systems.

More recently, rose growers are adopting the same system and are growing the bushes mostly in large plastic pots raised above the ground.

Although setting up infrastructure is around 40% higher than the traditional production system in ground beds, increased yields and better quality are paying off the investment. Carnation growers report a significant reduction of losses caused by *F. oxysporum,* particularly on those varieties which are highly susceptible, passing from loss levels as high as 45% to only 3% in one production cycle. Rose growers are reporting yield increases of 25% derived from higher production densities possible with this system and better plant health and vigour.

Regulatory agency acceptance

Restrictions have started to arise in relation to open air burning of rice hulls. Suppliers are now devising furnaces and other systems for burning in contained environments. In order to avoid soil contamination, the nutrient solution should be recirculated.

Were the treatments difficult to develop?

No. In general growers have successfully adapted the system from soilless and hydroponic production schemes that were already used in other countries such as the Netherlands and Israel. Selecting a good substrate that is also economical has required a good amount of experimentation.

Were the treatments difficult to implement?

Soil-less substrates require stricter monitoring of factors like fertilisation, pH and water management. Pest and disease control may require closer scouting (monitoring).

Applicability to other crops and regions

Cultivation in substrates has been used for many years in countries such as the Netherlands and Israel. Presently, there is a strong trend amongst flower and vegetable growers in many countries to shift to soilless substrates. There are examples of growers in Kenya, Costa Rica, Ecuador, Brazil, Zimbabwe and other countries that, using various substrates (e.g. composted pine bark, coconut coir, pumice stone), are successfully producing in substrates (Pizano 2001, 2002ab, UNEP 2001).

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9.4 Case studies on alternatives to MB for postharvest uses

Case study 22. Use of phosphine as a component of an integrated storage pest management programme

Phosphine can be as effective as methyl bromide for disinfesting milled rice in storage, although it is a slower treatment. Cotton sheets placed around bag stacks act as a barrier to insects and can reduce the need for refumigation.

Commodities Milled rice

Locations Indonesia and Vietnam

Pests Beetles including *Sitophilus* spp., T*ribolium castaneum*, *Oryzaephilus surinamensis, Rhyzopertha dominica, Ahasverus advena and Cryptolestes minutus*.
Moths including *Corcyra cephalonica*.

History

Rice is the major cereal crop grown in the Southeast Asian countries, Indonesia and Vietnam. The period of storage for milled rice in bag stacks varies from a few months to a year or longer depending upon the volume of crop produced and on the intended usage. Protection of rice against insect pest damage is particularly important because it usually undergoes little or no further processing after storage. Disinfestation measures involve fumigation with MB, or sometimes phosphine, and prophylactic application of contact insecticides to the store fabric but not to the rice itself. Under the prevailing storage conditions in Southeast Asia fumigation of rice is necessary approximately every three months. Unprotected rice in store rapidly becomes unacceptably infested in humid tropical conditions.

Potential commercial use

Solid phosphide formulations are available in many countries; they are used for disinfesting grains in storage in the Philippines, and regularly used for treating rice in Indonesia and Vietnam. Used in combination with fumigation, cotton sheets can be placed on bag stacks to act as barriers against reinfestation, and can be adopted for any stored commodity in any country, reducing the need for refumigation during extended storage periods (R. Taylor, pers. com. 2002). To date use of cotton sheeting has not been widely practised but there is interest in commercial adoption in both Indonesia and Vietnam. The principal factor in any decision to use cotton sheets will be the period of storage of a commodity, and whether or not refumigation is likely to be needed.

Description of alternatives

Phosphine is as effective as methyl bromide for disinfesting rice, the only disadvantage being the longer time-period necessary using phosphine. However, the time-period required could be reduced by up to 24 hours using a cylinder-based formulation of phosphine combined with carbon dioxide instead of using solid aluminium or magnesium phosphides. Carbon dioxide alone has been used for long term protection of carry-over stocks of bagged rice in Indonesia (MBTOC 1998, ASEAN 1991).

The frequency with which disinfestation becomes necessary during extended storage periods can be decreased by reducing the rate of reinfestation following fumigation. This can be achieved using a physical barrier against insect pests, such as a cotton covering sheet over bag stacks, a method evaluated in East Africa in the 1960s, and used in Mali in the 1980s for strategic stocks of grain (R. Taylor, pers. com. 2003). The use of cotton prevents moisture condensation under the sheet during storage even under hot and humid conditions, and there is no risk of fungal spoilage. Placing a layer of insecticide dust at floor level adjacent to the sheet and occasional insecticide spraying of the sides of the sheet, particularly at the floor level, ensures that insects do not crawl beneath the sheet. In practice, stacks are covered with the cotton sheeting prior to the fumigation process, and left in position after the fumigation is complete. Where regular size bag stacks are constructed, as in Indonesia, the use of a tailored (box construction) cotton sheet was found to be very effective and convenient. As part of an integrated storage pest management system, insect traps placed in the store and under the cotton sheet help to determine the effectiveness of the insect barrier and indicate any need for further fumigation.

Regulatory agency acceptance

No regulatory approval is necessary for use of cotton sheeting as a physical barrier against insect pests. Phosphine generated from aluminium or magnesium phosphides has been registered widely for many years. However, the use of cylinder-based phosphine gas may require separate regulatory approval.

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Information contributed by Mr. Robert Taylor

Case study 23. Use of vacuum-hermetic treatment for disinfestation of cocoa beans in Côte d'Ivoire

Products are placed in sealed, flexible PVC-based containers, which provide a high level of gas-tightness. A simple vacuum pump is used to withdraw air, creating a low pressure within the container. Complete mortality of insect pests is achieved in less than 3 days.

Crop/commodity Cocoa beans

Principal pests:

Ephestia cautella
Tribolium castaneum
Plodia interpunctella

History

Cocoa beans and similar stored products need to be fumigated during storage and prior to shipment for export, to maintain quality and prevent transfer of pests to the importing country. MB is the fumigant of choice prior to shipment because of its rapid and broad spectrum of action. Cocoa commodities are important for export earnings in several Article 5(1) countries, and must be free from pests to maintain their commercial value. The Volcani Center in Israel has developed a vacuum-hermetic system for controlling stored product pests. Commercial trials were conducted on cocoa beans in Côte d'Ivoire, in Boston, U.S.A. and in Israel.

Commercial use

The vacuum-hermetic system has been recently introduced to Côte d'Ivoire for cocoa beans.

Description of alternative

The commodities are placed in sealed, flexible PVC-based containers (called 'Volcani cubes' or 'GrainPro Cocoons'). These provide a high level of gas-tightness (Navarro *et al*. 1988). Sacks of cocoa beans are placed within the flexible containers, and a vacuum pump is used to withdraw air, creating a low pressure (between 23 and 75 mm Hg abs.) within the container.

The treatment is successful in achieving complete mortality of the insect pests in less than 3 days (Finkelman *et al*. 2002). The container also provides on-going protection for the products, preventing re-infestation and preventing loss or gain of moisture.

Regulatory agency acceptance

Registration is not needed for vacuum-hermetic treatment.

Were the treatments difficult to implement?

No.

Applicability to other uses and regions

Further work is needed to develop this treatment for other insects and commodities. Vacuum-hermetic disinfestations, often combined with other treatments such as raised temperatures or controlled atmospheres, appear to be promising for other high-value crops such as coffee, nuts, dried fruits and spices in both tropical and temperate climates around the world (Finkelman *et al.* 2002, Navarro *et al*. 2001, 2002).

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Case study 24. Use of heat and carbon dioxide for control of insects in dates in Israel

Experiments were carried out to investigate the influence of various modified atmospheres and low pressures in causing nitidulid beetles to emigrate from infested dried fruit, for which dates served as a model. Cold storage, and treatments with heat and carbon dioxide were evaluated for their effectiveness in controlling these beetles.

Crop/commodity: Dates

Pests

Carpophilus mutilatus
Carpophilus hemipterus
Carpophilus dimidiatus
Ephestia cautella
Haptoncus luteolus
Oryzaephilus surinamensis
Tribolium castaneum

History

Nitidulid beetles, and in particular *Carpophilus mutilatus* and *C. hemipterus*, are the most important pests of dates in Israel at the time of harvest. Upon arrival at the packing stations the dates are fumigated to control field infestations, and are then stored until processing, usually in cold storage to maintain date quality. This initial fumigation serves a twofold purpose; it stimulates the active insect stages (larvae and adults) to emigrate from the fruit before they succumb, and kills the insect population. The emigration of insects from fruit, before they are killed, is important for achieving the acceptable commercial limits on insect contamination in food.

Commercial use

A treatment based on carbon dioxide and heat has been introduced in Israel for the emigration/control of insects in dates, and is currently used by two agricultural cooperatives.

Description of alternative

Treatment to cause emigration of nitidulid beetles. Experiments were carried out to investigate the influence of various modified atmospheres and low pressures in causing nitidulid beetles to emigrate from infested dried fruit, for which dates served as a model. The most effective treatments were pressure of 100 mm Hg abs., 30% carbon dioxide or 2.8% oxygen in air, all of which caused over 80% of the initial insect populations to emigrate from the fruit after 4 hours exposure. The effect of heat at 40°C in causing emigration from the infested dates was also tested. While heat alone can induce emigration, it was less effective than the other treatments (S. Navarro, pers. com, 2002).

Treatments for the control of nitidulid beetles. *Cold treatments*: Storage at 0°C and -5°C is relatively inefficient for control of the *Carpophilus* species, particularly since rates of cooling of the dates, and the form and size of packaging, must be taken into consideration. Conversely, mortality at -10°C and -18°C is extremely rapid, and shortly after the centre of the date container reaches these temperatures, complete control occurs. In situations where cold penetration is rapid, as in the case of unpacked dates, this treatment would be sufficient to control any field infestations by two *Carpophilus* species which are not removed during the disinfestation treatment.

Heat treatments: Heat alone, in the range of 45°-50°C, can cause death of insects within several hours. However, the effect on the quality of the dates and its drying effect must be considered. The Deglet Noor variety of dates was found to be resistant to discoloration during short exposures of several hours at 55°C. Therefore, it was found that a combination of heat and carbon dioxide treatment is desirable to enhance mortality and emigration of the pests.

Carbon dioxide treatment: The effectiveness of 60-80% carbon dioxide within a 151 m^3 plastic chamber filled with dates stacked in crates on pallets was demonstrated. At the initial purge phase the desired carbon dioxide concentration can be achieved in the chamber within one hour by introducing the gas under high pressure. Date quality is not affected and the insect population is effectively controlled. This technology is suitable for the treatment of dates to control pests and maintain quality (Navarro *et al.*, 1998, 2000).

Regulatory agency acceptance

Registration is not needed in Israel for heat treatment, nor for a modified atmosphere that uses carbon dioxide.

Were the treatments difficult to implement?

No. For carbon dioxide treatment, a supply of the gas in cylinders or from a tanker supply is necessary.

Applicability to other uses and regions

The application of carbon dioxide at elevated temperatures is likely to be suitable for other regions of the world that grow dates. This technology could also be adapted for other dried fruit such as figs, raisins etc. Trials on dried figs in Turkey found that the combination of about 96% CO_2 + and raised temperature (30°C) provided disinfestation of *Plodia interpunctella* (larvae), *O. surinamensis* (adults and eggs) and *Carpoglyphus lactis* (mixed stages) in dried figs, while *T. granarium* was controlled by 99% CO_2 at 37°C (S. Navarro, pers. com, 2002).

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Case study 25. Use of vacuum-hermetic treatment for disinfestation of narcissus bulbs as a quarantine treatment in Israel

Bulbs are placed in a chamber made of a flexible liner that can hold vacuum or modified atmospheric gas compositions.

Crop/use Narcissus bulbs

Pests *Merodon eques*

History

The large narcissus fly, *Merodon eques*, is a quarantine insect species that attacks narcissus bulbs as well as bulbs of other geophytes. Fumigation with methyl bromide provides a rapid treatment for infested bulbs. However, as a result of the Montreal Protocol and the phytotoxic effects of MB and some other fumigants, there was impetus to develop a new disinfestation method. Pilot commercial experiments were initially conducted in Israel using a newly developed vacuum-hermetic fumigation system.

Current commercial use

As a result of this work, the vacuum-hermetic system has recently been introduced for disinfestation of narcissus bulbs in Israel.

Description of alternative

This vacuum-hermetic system consists of a chamber made of a flexible liner that can hold vacuum or modified atmospheric gas compositions. The bulbs are placed in the chamber on their original shipping pallets using a forklift. The desired modified atmosphere is achieved by taking advantage of the respiration of the narcissus bulbs, which under hermetic sealed conditions result in a rapid reduction in oxygen to 0.1% within 18 hours at 30ºC, while the carbon dioxide concentration increases up to 21%. The system is sealed for about 48 hours to ensure a successful treatment. Laboratory trials were conducted for several years to ensure that the narcissus bulbs are capable of creating such atmospheres in the vacuum-hermetic system, and that the large narcissus fly can be controlled as a result of this atmosphere (Finkelman *et al.* 2002, Navarro *et al.* 1997ab).

Regulatory agency acceptance

Registration is not needed for vacuum-hermetic treatments in Israel.

Were the treatments difficult to implement?

No.

Applicability to other uses and regions

Hermetic disinfestation is likely to be suitable for many commodities. Treatment conditions within the vacuum-hermetic system can be adapted to the application of modified atmospheres, vacuum or heat treatment, according to the special needs of the treated commodity.

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Case study 26. Use of cleaning, pest monitoring, trapping and targeted pesticides in food facilities in Hawaii

The pest control system is based on exclusion of pests where possible, regular cleaning, a high standard of hygiene, inspection of incoming stock, regular stock rotation, and early detection and removal of pests.

Crop/use Food warehouses, food processing facilities

Pests		
	Cigarette beetle	*Lasioderma serricorne*
	Red flour beetle	*Tribolium castaneum*
	Indianmeal moth	*Plodia interpunctella*
	Almond moth	*Ephestia cautella*
	Lesser grain borer	*Rhyzopertha dominica*
	Rice weevil	*Sitophilus oryzae*
	Book lice	Psocid species

History

Food warehouses in Hawaii often hold large consignments of imported high-value food products such as rice, nuts, dried fruit, spices, candy, pasta, pet foods and a variety of flour-based products. Potential infestation of these foods during storage is a major concern to companies involved in food manufacturing, warehousing and distribution. Stored product pests can breed rapidly all year round in Hawaii's tropical climate. Most food facilities are left partially open for ventilation, making them particularly susceptible to new infestations from outside. A major food warehouse decided not to use MB, and has adopted an extensive hygiene and pheromone trapping programme.

Current commercial use

This IPM method is used in HFM FoodService, one of the largest food distribution companies in Hawaii.

Description of the alternatives

The alternative pest control system is based on exclusion of pests where possible, a high standard of hygiene, inspection of incoming stock, regular stock rotation, and early detection and removal of pests. They employ pest trapping and monitoring, insect suppression techniques, and targeted or localized pest control products both within and outside the food premises. The result is that pest numbers are not able to build up to problem levels, so that fumigation is not required (Pierce 2000, Raynaud 2002).

Regulatory agency acceptance

No regulatory approval is needed for the IPM system. Pest control products used in the system are registered products.

Were the treatments difficult to implement?

No. The company trained all the relevant staff, and receives regular visits from a pest control specialist.

Applicability to other uses and regions

IPM programmes of this kind can be used in many different climates, including cool regions such as Scandinavia (Nielsen 2000). Similar IPM programmes are also used instead of MB fumigation in food processing facilities and flour mills in Europe, the USA and Canada (Case study 27).

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Case study 27. Use of IPM and heat treatments in food processing facilities in Europe, USA and Canada

Equipment and parts of buildings are adjusted to exclude pests and remove pest harbourages in and around the building to the extent possible. Regular and thorough cleaning and inspection programmes are established.

Crop/use

Food processing facilities, pet food processing, flour milling, warehouses

Target pests

- Beetles such as the warehouse beetle, rust-red grain beetle, rust red flour beetle, confused flour beetle, sawtoothed grain beetle.
- Weevils such as granary weevil, rice weevil and maize weevil
- Moths such as Indianmeal moth, tobacco moth and Mediterranean flour moth
- Mites
- Filth flies
- Ants
- Rats and mice
- Birds

History

The food processing industry has a very high economic value. The climate found within food processing facilities is frequently warm and sometimes moist, providing good conditions for insects and other pests to multiply. Incoming raw ingredients and many different suppliers can deliver pests to the facilities or warehouses. MB is often used for pest control because it is able to penetrate into difficult-to-reach parts of equipment and crevices in the fabric of the building. However, large food processing and milling facilities in Europe, Canada and the USA have introduced systems of rigorous cleaning, inspection, and targeted pest control products, that control pests and avoid the need for fumigation. Heat treatments are also carried out in some cases.

Commercial use

Modern IPM systems are used instead of MB fumigation in mills and food processing facilities around Europe and North America. In the UK, for example, FritoLay, a large international snack food processing facility, uses a cost-effective IPM system based largely on preventive cleaning and inspection as an alternative to MB (Raynaud 2002). In the USA, examples include companies such as Kellogg, KanKan, Nestlé Purina, FritoLay and pharmaceutical companies (Mueller 2003), a milling and processing plant of 74,300 m^2 that produces snack foods, and a plant of 27,800 m^2 that produces pet foods (Corrigan 2002a).In Canada, Griffith Laboratories, which manufactures a wide variety of food ingredients, has replaced MB with an IPM system that emphasises sanitation, monitoring, trapping and careful supplier selection (MBIGWG 1998). Rogers Food operates a flour mill in Canada that uses careful and thorough sanitation to avoid the need for MB (MBIGWG 1998). Quaker Oats of Canada, for example, uses sanitation programs and heat treatments in their cereal milling and processing facility, part of which is 100 years old and constructed of timber posts, wooden floors and stone walls (Sheppard 1998, MBIGWG 1998). Pillsbury has also used IPM + heat for a number of years, and the company's pest control manager has noted that heat sterilization has proven to be extremely successful (Heaps 1998). Several other North American food companies, such as Nabisco, Con Agra, General Mills, Nestlé Purina, Lauhoff and Seimer Milling, have also used heat treatments to eliminate insects from their facilities (Heaps 1998, Mueller 2003). As a result of these IPM programmes, many facilities have not used MB for almost a decade (Stanbridge 2002a, Mueller 2003).

Description of alternative

Equipment and parts of buildings are retrofitted and adjusted to exclude pests and remove pest harbourages in and around the building to the extent possible. Regular and thorough cleaning and inspection programmes are established. This is accompanied by trapping, pest monitoring, inspection of incoming stock, and use of bait stations, targeted insecticides and other pest controls products as necessary. These combined activities deny pests shelter, access, food, and a time interval in which to breed. Well-designed programmes achieve all the commercial pest control standards and regulatory requirements. A major European snack food producer has noted that well-designed cleaning and inspection programmes within a food facility prevent insect development, reduce the risk of foreign object contamination and provide support for a sound 'due diligence' programme to meet commercial and regulatory standards for food safety (Raynaud 2002). In the US, these IPM programmes allow producers to more easily achieve the 'filth standards' that limit the quantity of insect fragments, rodent hairs etc. allowed in food products, by focussing on the prevention of contamination instead of fumigating after contamination has occurred (Corrigan 2002ab). Heat treatments provide additional forms of pest control in some cases(Sheppard 1998, Heaps 1998, MBIGWG 1998).

Acceptance by regulatory agencies

Cleaning, sanitation activities and heat treatments do not require registration. The pesticides used are registered products. Heat, thorough cleaning and pest-contaminant prevention programmes are very acceptable to supermarket purchasers and consumers.

Were the treatments difficult to implement?

No. Management support for the change is essential (Stanbridge 2002a). The system requires good staff training, a change in staff attitude and practices, and proper daily management. Some structures are not suitable for the use of heat for pest control. Effective heat disinfestations requires a very good understanding of heat transfer and distribution in a building, and knowledge of other methods for dealing with 'cold' areas such as cellars or cracks.

Applicability to other uses and regions

These IPM systems can be adapted to suit a wide range of climates, pests and facilities. IPM programmes of various kinds – without MB fumigation - are used in food facilities in diverse climates from the humid tropics of Hawaii (Case study 26) to cool regions of Scandinavia (Nielsen 2000).

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Case study 28. Use of low dose phosphine + carbon dioxide + heat in food processing facilities and flour mills in North America and Europe

The combination of 2% phosphine in carbon dioxide (‘Eco$_2$Fume’) + heat (30-35°C) has been used in food facilities since the mid-1990s. Structures are sealed tightly and heated and the gases are released into the structure. Raised temperature and CO_2 increase the susceptibility of the pests to phosphine.

Sector

Food processing facilities, flour mills, warehouses, storage structures

Principal target pests

- Indianmeal moth (*Plodia interpunctella*)
- Mediterranean flour moth (*Ephestia kuehniella*)
- Navel orangeworm (*Amyelois transitella*)
- Yellow mealworm (*Tenebrio molitor*)
- Red flour beetle (*Tribolium castaneum*)
- Confused flour beetle (*Tribolium confusum*)
- Cigarette beetle (*Lasioderma serricorne*)
- Drugstore beetle (*Stegobium paniceum*)
- Sawtoothed grain beetle (*Oryzaephilus surinamensis*)
- Warehouse beetle *(Trogoderma variabile*)
- Lesser grain borer (*Rhyzopertha dominica*)
- Granary weevil (*Sitophilus granarius*)
- Rice weevil (*Sitophilus oryzae*)
- Rats, mice, birds

History

Control of insects and other pests in food processing facilities and mills is necessary for meeting strict commercial and regulatory standards. These facilities provide a desirable environment for pests to shelter and breed, leading to substantial economic losses if left uncontrolled. In response to the Montreal Protocol’s controls on MB, a US fumigation company, Fumigation Service and Supply Inc. developed an alternative fumigation system based on low levels of phosphine in combination with heat and carbon dioxide (Mueller 1998). The method was patented in 1995 (US patent # No. 5,403,597).

Commercial use

About 70 structural fumigations of food facilities and flour mills have been carried out using phosphine + carbon dioxide + heat in the USA and Canada (Mueller 2002). Examples of treated facilities include Nabisco, Hills Pet Nutrition, Star of the West Milling, Pillsbury, General Mills, Monsanto and Quaker Oats Canada (Mueller 2003).This alternative has also been used for fumigation of three food premises in Europe (Italy, Germany and Denmark), and more are planned. In North America and Europe, a number of fumigation companies have been trained how to carry out this combination fumigation, including the necessary methods of corrosion management.

Description of alternative

'Eco$_2$Fume' comprises 98% carbon dioxide (recycled from industrial processes such as fermentation) + 2% phosphine + heat (30-35°C). The facilities are prepared by removing or sealing equipment that may be sensitive to phosphine. The structure is sealed tightly. The building is heated to the required temperature and the gases are released into the structure. The fumigation typically takes 24 – 36 hours in total compared to 24 – 48 hours for a typical MB fumigation.

About 70 fumigations carried out in food facilities have been intensively monitored. Controlled trials involving government agencies and private fumigation companies in a large flour mill in Canada, for example, found a 99.22% mortality of mixed stages of five species of stored product insects, and 97.4% mortality achieved in mixed stages of flour beetles in a 3m tube filled with oat flour in 33 hours (Mueller 1998; Agriculture and Agri-Food Canada 1996). Research and commercial practice has shown that this treatment is as effective as typical MB fumigations in food processing facilities and mills.

Acceptance by regulatory agencies

'Eco$_2$Fume' was registered by the US EPA in 2000. Phosphine is registered for food facilities and milling in more than 100 countries (Mueller 2002).

Were the treatments difficult to implement?

The handling of these three factors demands a high level of skill, and requires a well trained specialist fumigator. Advanced training is necessary to ensure effective management of the fumigation and to avoid phosphine corrosion of copper in equipment.

Applicability to other uses and regions

The combination of phosphine + CO_2 + heat could be used in any country where a supply of CO_2 and heat can be obtained.

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Appendix

1

Methyl Bromide Technical Options Committee - Committee Structure

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MBTOC structure as at 31 December 2002

Cochairs

Dr Jonathan Banks — Consultant, Australia

Dr Nahum Marban Mendoza — Universidad Autonoma de Chapingo, Mexico

Subcommittee chairs, chapter lead authors for this Assessment

Chapter 1 - Executive summary

Chapter 2 - Introduction to the Assessment - lead author, Dr Jonathan Banks.

Chapter 3 - Methyl bromide production, consumption and limitations on use - lead author, Dr Melanie Miller.

Chapter 4 - Alternatives to methyl bromide for soil treatment - chair of 'soils' subcommittee and lead author, Dr Ian Porter.

Chapter 5 - Alternatives for treatment of durables, wood products and structures - cochairs of 'durables' subcommittee and lead authors - Drs Chris Bell and Christoph Reichmuth.

Chapter 6 - Alternatives evaluated in Article 5(1) countries – Response to Decision IX/5(1e) - Cochairs of the 'Article 5' subcommittee, Dr David Okioga and Ms Marta Pizano, lead authors, Ms Marta Pizano and Dr Melanie Miller.

Chapter 7 - Alternatives to methyl bromide for quarantine and pre-shipment applications - chair of the 'QPS' subcommittee and lead author, Dr Tom Batchelor.

Chapter 8 - Reducing methyl bromide emissions - chair of the '3R' subcommittee and lead author, Dr Don Smith.

Chapter 9 - Case studies on commercial adoption of alternatives to MB - lead authors, Ms Marta Pizano and Dr Melanie Miller.

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