Environmental and
Health Impacts of
Pesticides and
Fertilizers and Ways
of Minimizing Them

Envisioning A
Chemical-Safe World

Chapter 7 of 12

Status and trends of fertilizer use

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About

In December 2017, Resolution 4 of the 3rd Session of the United Nations Environment Assembly (UNEA 3) requested “the Executive Director to present a report on the environmental and health impacts of pesticides and fertilizers and ways of minimizing them, given the lack of data in that regard, in collaboration with the World Health Organization (WHO), the Food and Agriculture Organization of the United Nations (FAO) and other relevant organizations by the fifth session of the United Nations Environment Assembly”. In response to this request, UNEP published a *Synthesis Report on the Environmental and Health Impacts of Pesticides and Fertilizers and Ways to Minimize Them*[1] in February 2022 (United Nations Environment Programme [UNEP] 2022).

The overall goal of the synthesis report is to provide the information base to enable other advocacy actions to be taken by stakeholders to minimize the adverse impacts of pesticides and fertilizers. Specific objectives of the synthesis report are to:

- Update understanding of current pesticide and fertilizer use practices;
- Present major environmental and health effects of pesticides and fertilizers, during their life cycle, and identify key knowledge gaps;
- Review current management practices, legislation and policies aimed at reducing risks in the context of the global chemicals, environmental and health agenda;
- Identify opportunities to minimize environmental and health impacts, including proven and innovative approaches.

This chapter on “The regulatory and policy environment for pesticide management” is the 7th in a series of 12 chapters that make up a comprehensive compilation of scientific information. The chapters were developed to both inform and further elaborate on the information provided in the synthesis report. Please note that the disclaimers and copyright from the synthesis report apply.

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[1] The Synthesis report is available at https://www.unep.org/resources/report/environmental-and-health-impacts-pesticides-and-fertilizers-and-ways-minimizing.

Status and trends of fertilizer use

7

7.1 Overview

Soil is a major source of nutrients needed for plant growth. However, it may not provide adequate amounts of all the essential nutrients that plants require in correct proportions. Fertilizers can address nutrient deficiencies, maintain soil fertility, support crop growth, and maximize economic returns. [Chapter 7.2.1] They are loosely grouped as inorganic and organic, depending on their source and how they are produced. Nitrogen, phosphorus and potassium are the primary nutrients which fertilizers supply (Fairhurst 2012; Abdou *et al*. 2016; European Union [EU] 2019). [Chapter 7.2.2]

Enhanced efficiency fertilizers (EEFs) can play a significant role in sustainable agricultural production, but they may be expensive and some of the coating materials used are non-degradable (Naz and Sulaiman 2016). Moreover, EEFs may not perform better than conventional fertilizers (Li, T. *et al*. 2017). Research gaps exist for some of these fertilizers. [Chapter 7.2.4] Nutrient losses can be reduced by taking the state of the soil into account (Johnson and Bruulsema 2014), targeting plant requirements, applying the right fertilizer, adopting practices that improve nutrient use efficiency (Johnson and Bruulsema 2014; Nkebiwe *et al*. 2016; Wohab *et al*. 2017; Mutegi, Kiwia and Zingore 2019), and using good storage practices (Teenestra *et al*. 2015; Albadarin, Lewis and Walker 2017; Ndambi *et al*. 2019). [Chapters 7.2.6, 7.2.7]

About 190 million tons of inorganic fertilizer was used in agriculture in 2018 (Food and Agriculture Organization of the United Nations [FAO] 2020a). By 2025 demand for inorganic fertilizer for agricultural use is expected to reach 208 Mt (International Fertilizer Association [IFA] 2021a). [Chapter 7.3.2] Only a small fraction of organic waste materials (e.g., 5 per cent in the European Union) is used as fertilizer (United Nations Environment Programme [UNEP] 2019). Proper waste treatment, combined with recycling, has the potential to reduce demand for inorganic fertilizers (Christodoulou and Stamatelatou 2016; Schneider *et al*. 2019; Rutgersson *et al*. 2020). [Chapter 7.2.5]

Use of both inorganic and organic fertilizers for crop production tends to be rather high in some countries. In a number of them, estimates of nitrogen from inorganic and organic fertilizers are more than 200 kg of nitrogen per hectare (ha) of cropland per year (FAO 2020b). However, fertilizers use is particularly low in sub-Saharan Africa (SSA) (e.g., <50 kg N/ha/year) (Sutton *et al*. 2013). [Chapter 7.3.2]

The nitrogen in inorganic fertilizers is derived using the Haber-Bosch artificial nitrogen fixation process (Erisman *et al*. 2008). However, nitrogen and other nutrients can be recycled or transferred through the use of organic inputs (e.g., manure) (Fairhurst 2012; Bouwman *et al*. 2013; FAO 2020a; FAO 2020b). [Chapter 7.3.2]

Annually, livestock manure left on pasture and applied to soil contains about the same amount of nitrogen as that used from inorganic fertilizers (FAO 2020a; FAO 2020b). Manure probably contributes at least half the phosphorus used in crop and pasture production (Bouwman *et al*. 2013). The amount of manure nitrogen left in pastures could be about three times the amount applied to soil (FAO 2020b). [Chapter 7.3.2]

The amount of applied nitrogen taken up by cereal plants during the first year of fertilizer application can range from 30-50 per cent. In well-managed fields cereals take up about 40-65 per cent of fertilizer nitrogen, 15-25 per cent of fertilizer phosphorus, and 30-50 per cent of fertilizer potassium in the first year of application. Subsequent crops benefit from some of the fertilizer nutrients left in the soil by the first crop. For example, most of the phosphorus applied can be used by subsequent crops. [Chapter 7.4.1]

Fertilizers should be handled with care during transportation, storage and field application to avoid losses and exposure to hazards. [Chapters 7.2.6, 7.2.7, 7.2.8, 7.4.1, 7.4.2]

The fertilizer distribution chain is especially long in SSA, above all in landlocked countries. In general, fertilizer prices are highest in SSA compared with other regions. A large portion of retail costs are for transport, as fertilizer is mostly carried by road within countries and throughout the continent (Wanzala and Groot 2013; Gro Intelligence 2016; Benson and Mogues 2018) [Chapters 7.4.3, 7.4.4, 7.5.1]

Direct drivers that tend to increase the use of fertilizers include fertilizer subsidies, practices and technologies that make fertilizer use profitable, access to input credit and markets for inputs and produce and use of information and communication technology. Factors that can contribute to decreased fertilizer use include policies, practices and technologies that improve nutrient use efficiency, as well as dietary choices and efforts to reduce food loss [Chapters 7.5.1, 7.5.2].

7.2 Types of fertilizers and fertilizer management

7.2.1 The nutrients required by plants

To grow well, plants require an adequate supply of primary nutrients (nitrogen [N], phosphorus [P] and potassium [K]), secondary nutrients (calcium [Ca], magnesium [Mg], sodium [Na] and sulphur [S]), and micronutrients or trace elements (boron [B], copper [Cu], chlorine [Cl], iron [Fe], manganese [Mn], molybdenum [Mo] and zinc [Zn]) (EU 2019). Primary and secondary nutrients are also referred to as "major nutrients" or "macronutrients" (Roy *et al*. 2006).

Soil is a main source of nutrients, but it may not provide adequate amounts of all the nutrients required by plants in the correct proportions. Fertilizers can be applied to address deficiencies in essential nutrients, maintain soil fertility, support productive and nutritious crops, and maximize economic returns.

7.2.2 Major fertilizer types

Fertilizers are loosely grouped as inorganic or organic, depending on how they are produced and their sources. Fertilizing products can also be grouped into a larger number of categories. For example, in the 2019 European Union (EU) regulation concerning the marketing of fertilizing products, Annex I on Product Function Categories (PFCs), seven PFCs are designated: 1) fertilizer (organic, organo-mineral and inorganic); 2) liming material; 3) soil improver (organic and inorganic); 4) growing medium; 5) inhibitor; 6) plant biostimulant; and 7) fertilizing product blend (European Union [EU] 2019).

Inorganic and organic fertilizers, organo-mineral fertilizers (which combine inorganic and organic fertilizers), biostimulants (products that stimulate plant growth but do not provide nutrients) and enhanced efficiency fertilizers (whose sources can be inorganic or organic) are described below.

Inorganic fertilizers

Inorganic fertilizers are nutrient-rich. They are produced industrially by chemical processes, mineral extraction or mechanical grinding (FAO 2019a). They are also referred to as "mineral fertilizers", "synthetic fertilizers" (when they are the result of a chemical process), "chemical fertilizers" and "conventional fertilizers". Urea, which provides nitrogen, is a "synthetic organic fertilizer" (University of Tennessee 1999) which is usually considered an inorganic fertilizer (Fairhurst 2012).

Inorganic fertilizers can be "straight fertilizers" (containing declarable amounts of only one of the three primary nutrients N, P and K) or "compound fertilizers" (containing declarable amounts of at least two of these nutrients) (FAO 1991). The 2019 EU regulation defines a "straight solid inorganic macronutrient fertilizer" as one with a declared content of either one macronutrient (N, P, K, Ca, Mg, Na, S) or only one primary macronutrient (N, P, K) and one or more secondary macronutrients (Ca, Mg, Na, S); it defines a "compound solid inorganic macronutrient fertilizer" as one with a declared content of more than one primary macronutrient (N, P, K) or more than one secondary macronutrient (Ca, Mg, Na, S) and no primary macronutrient (N, P, K) (EU 2019, pp. L 170/45-L 170/46).

Solid compound inorganic fertilizers may be further divided into "mixed fertilizers", produced by a physical process, and "complex fertilizers", produced by a process of chemical reaction (FAO 1991). All the nutrients in complex fertilizers are present in the same granule.

Globally, the inorganic fertilizers most commonly used in agriculture include urea, NPK fertilizers, ammonium phosphates and potassium chloride. Inorganic fertilizers that do not contain nitrogen, phosphorus or potassium include those supplying magnesium (e.g., dolomite), boron (e.g., boric acid), copper (e.g., copper sulphate), iron (iron sulphate), manganese (sulphate of manganese), molybdenum (ammonium molybdate) and zinc (zinc sulphate) (Fairhurst 2012).

Organic fertilizers

Organic fertilizers are derived from once-living organisms and are rich in carbon. They include animal manures (the most important fertilizer input for agricultural soils in many countries), composts, sewage sludge, green manures, peat, crop residues and by-products of industries handling agricultural produce (Codex Alimentarius Commission 2013). It should be noted that the use of nutrient sources like manures and crop residues entails the recycling of nutrients, and that the transfer of nutrients can occur, for example between fields and between farms.

Many organic fertilizers are used as soil amendments since they improve the soil's physical fertility (e.g., providing higher porosity or better infiltration capacity) and biological properties, as well as being a steady source of nutrients (Edmeades 2003; Abdou *et al.* 2016).

Organic fertilizers can largely be categorized as belonging to one of two groups: those that are end-products of processing, for example composts and digestates (Weithmann *et al.* 2018), and those that are used unprocessed, such as fresh livestock manures applied to the soil, green manures (e.g., cover crops) and crop residues left in the field.

Industrial processing of organic fertilizers presents an opportunity for refinement. For example, it makes possible products with higher and more reliable (instead of variable) nutrient concentrations, as well as the removal of certain contaminants.

Organo-mineral fertilizers

Organo-mineral fertilizers are a combination of organic and inorganic fertilizers (Kominko, Gorazda and Wzorek 2017). They probably represent a very small share of the global fertilizer market. Their market value is about 2 per cent of that of all fertilizers sold in the EU (European Commission 2016; Fertilizers Europe 2019).

Biostimulants

Biostimulants are not fertilizers *per se*. According to the definition in the International Code of Conduct for the Sustainable Use and Management of Fertilizers (FAO 2019a), they are products that stimulate plant growth through the synthesis of growth-promoting substances and/or plant nutrition processes independently of nutrient content; their aim is to improve plant nutrient use efficiency or uptake, plant tolerance to abiotic stress, or crop quality traits. While biostimulants (according to the 2019 EU regulation) "are not as such inputs of nutrients, [they] nevertheless stimulate plants' natural nutrition processes. Where such products aim solely at improving the plants' nutrient use efficiency, tolerance to abiotic stress or quality traits, or increasing the availability of confined nutrients in the soil or rhizosphere, they are by nature more similar to fertilizing products than to most categories of plant protection products. They act in addition to fertilizers, with the aim of optimizing the efficiency of those fertilizers and reducing the nutrient application rates" (EU 2019, p. L 170/4).

Diverse organic and inorganic substances and/or microorganisms can be considered biostimulants (Rouphael and Colla 2018; EU 2019). Examples of biostimulants include seaweed extracts, humic substances, amino acids, bacteria that promote plant growth (Halpern *et al.* 2015) and inorganic salts (Torre, Battaglia and Caradonia 2016).

7.2.3 Cropping systems and fertilizer use

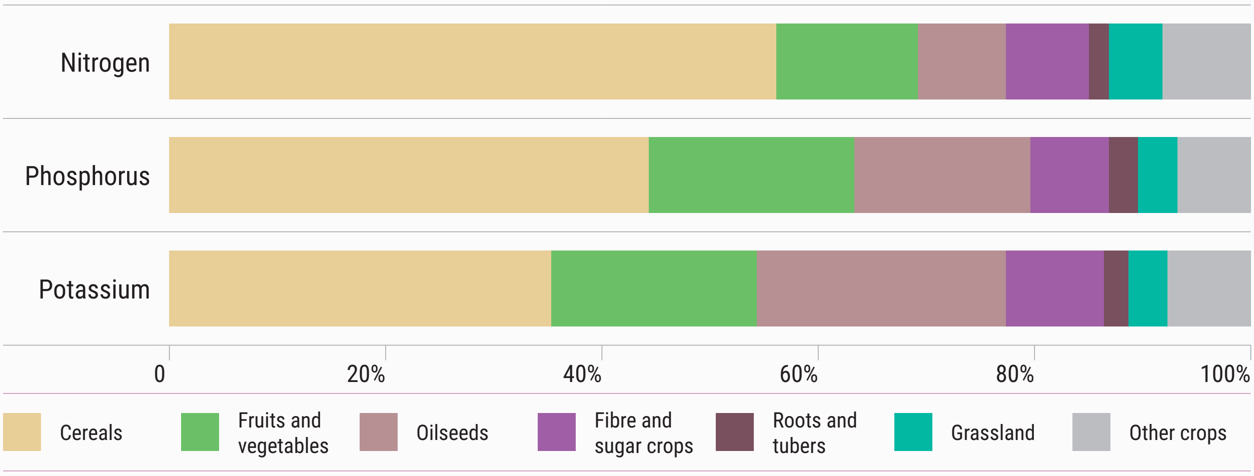
Of the fertilizers applied to crops globally, about half (49 per cent) are applied to cereals, 16 per cent to fruits and vegetables, and 13 per cent to oil crops (Heffer, Guère and Roberts 2017) (Figure 7.2-1). Partitioning of fertilizers among crops varies from one country to another. For example, about 32 per cent and 4 per cent of the N fertilizer used in China and India, respectively, were reported to be applied to fruits and vegetables (Heffer, Guère and Roberts 2017).

Global data on partitioning of organic fertilizers among crops are lacking. One study has reported that compared with wheat-maize rotation, greenhouse vegetables received about four times more N from inorganic fertilizer and about 30 times more N from manure in farmers' fields in China (Ju *et al.* 2007).

7.2.4 Enhanced efficiency fertilizers

Enhanced efficiency fertilizers (EEFs) have been defined by the Association of American Plant Food Control Officials (AAPFCO) as "fertilizer products with characteristics that allow increased plant uptake and reduce the potential of nutrient losses to the environment (e.g., gaseous losses, leaching, or run-off) when compared with an appropriate reference product" (Halvorson *et al.* 2014). They allow slow release or prolonged availability

Figure 7.2-1 Proportion of nutrients used by crop categories globally. Heffer, Guère and Roberts (2017).



of nutrients to plants. However, according to a review of the use of EEFs in nitrogen management (Li, T. *et al*. 2017), they do not always have higher use efficiencies than conventional fertilizers and they can sometimes be less efficient. The authors reported that the effectiveness of EEFs depends on the type of fertilizer, the cropping system and biophysical conditions. They concluded that while EEFs can play a significant role in sustainable agricultural production, prudent use of these fertilizers requires eliminating fertilizer mismanagement and implementing knowledge-based N management practices.

EEF systems can be categorized based on type of coating material (organic-and inorganic), mode of action (including urease activity inhibition and nitrification inhibition), composite nutrient formulations, use of naturally occurring minerals or their synthetic versions, and the technologies used in their development (e.g., nanotechnology) (Dimpka *et al*. 2020). Those already on the market or under development include controlled release fertilizers, slow release fertilizers, stabilized fertilizers and nanofertilizers.

Controlled release fertilizers

Controlled release fertilizers (CRFs) are mostly urea and NPK based (Mordor Intelligence 2021a). They are coated with a polymer (typically resin, plastic or biopolymers), which facilitates nutrient release according to plant requirements at different growth stages over weeks to months (Trenkel 2010; International Fertilizer Association [IFA] 2017). Examples of CRFs include polymer coated urea, polymer-sulphur coated urea, and polymer coated NPK (Mutegi, Kiwia and Zingore 2019).

CRFs typically require a minimum level of persistence in the environment (12-18 months) to achieve their intended purpose (European Chemicals Agency 2019). An issue with these fertilizers could be the degradation rate of the coating material. For example, the criteria for polymers in the 2019 EU fertilizer regulation include the requirement that at least 90 per cent of the organic carbon should be converted into carbon dioxide (CO_2) no more than 48 months after the end of its claimed functionality period (EU 2019, L 170/131). However, some of the coating materials used are non-degradable (Naz and Sulaiman 2016). Coated fertilizers also tend to be more expensive than traditional ones (Naz and Sulaiman 2016).

Slow-release fertilizers

Slow-release inorganic fertilizers are not coated with polymers, but they release their nutrients (e.g., condensed chemical forms of urea) slowly, over weeks to months (Trenkel 2010; IFA 2017). They can also have organic sources (Mutegi, Kiwia and Zingore 2019).

Urea supergranules/briquettes (weighing about 1-3 grams), used together with Urea Deep Placement (UDP) technology, are an example. This technology was developed by the International Fertilizer Development Center (IFDC) and its collaborators to reduce nitrogen losses. It is mainly used in the production of irrigated rice in Bangladesh (International Fertilizer Development Center [IFDC] 2017). Urea supergranules can also contain phosphorus and potassium (Chien, Prochnow and Cantarella 2009).

Another example is direct application of phosphate rock. According to several authors (Chien *et al*. 2011), the solubility of phosphate rock varies depending on its source. Although the application of slow release types may not be a suitable option for annual crops, it could be suitable for perennials in acid soils where rainfall is prevalent (Weeks and Hettiarachchi 2019). In addition, partial acidulation of phosphate rock has been reported to improve phosphate use efficiency (Bationo and Kumar 2002).

Stabilized fertilizers

Stabilized fertilizers are nitrogen fertilizers to which urease inhibitors and/or nitrification inhibitors are added (Trenkel 2010; Ribeiro *et al*. 2016; IFA 2017). For example, neem oil, which is known to have nitrification inhibition properties, is used to coat urea in India (Singh 2016). A meta-analysis of the effect of urease and nitrification inhibitors reported improved crop yields and improved nitrogen use efficiency, but their effectiveness depended on environmental and management factors

(Abalos *et al*. 2014). In meta-analyses, nitrous oxide (N_2O) emissions were less for fertilizers with both urease and nitrification inhibitors than for fertilizers without inhibitors, while urease inhibitors alone did not appear to reduce emissions (Snyder *et al*. 2014).

Nanofertilizers

Nanofertilization is a recent technology that involves the use of particles approximately 1-100 nanometres in size (Mikkelsen 2018). (One nanometre is one billionth of a metre.) Fertilizers (e.g., urea fertilizers) can be coated with nanomaterials to reduce the rate of dissolution of nutrients (Duhan *et al*. 2017; Iqbal, Umar and Mahmooduzzafar 2019).

Studies have suggested that nanofertilizers could be more beneficial than conventional fertilizers. Nanotechnology can enhance crop productivity and reduce nutrient losses (Dimkpa and Bindraben 2018). Coating microbial plant biostimulants with plyometric nanoparticles can improve their shelf life (Duhan *et al*. 2017). Zinc applied to leaves has a low degree of penetration and limited mobility in the phloem. Nanotechnology can improve plant uptake and movement in the phloem when the zinc is applied to plant leaves (Rios, Garcia-Ibañez and Carvajal 2019).

Despite the potential benefits of nanotechnology, its use by farmers could be constrained by lack of technical know-how as well as by economic factors (Hosseini, Nazrai and Lashgarara 2011). In India farmers may soon have access to nanofertilizers, as they have been researched and developed in that country and there are plans to apply them on farms under controlled conditions (*The Economic Times* 2019). According to Dimkpa and Bindraban (2018), large-scale industrial production of nanofertilizers has yet to take off. Furthermore, there is need to develop multi-nutrient fertilizers that provide balanced nutrition to plants and humans (Dimpka *et al*. 2020). At the same time, the possibility of negative effects and a paucity of research information on this technology have raised concerns among some scientists (Achari and Kowshik 2018; Dimkpa and Bindraban 2018; Kah *et al*. 2018; Zulfiqual *et al*. 2019).

7.2.5 Nutrient recycling

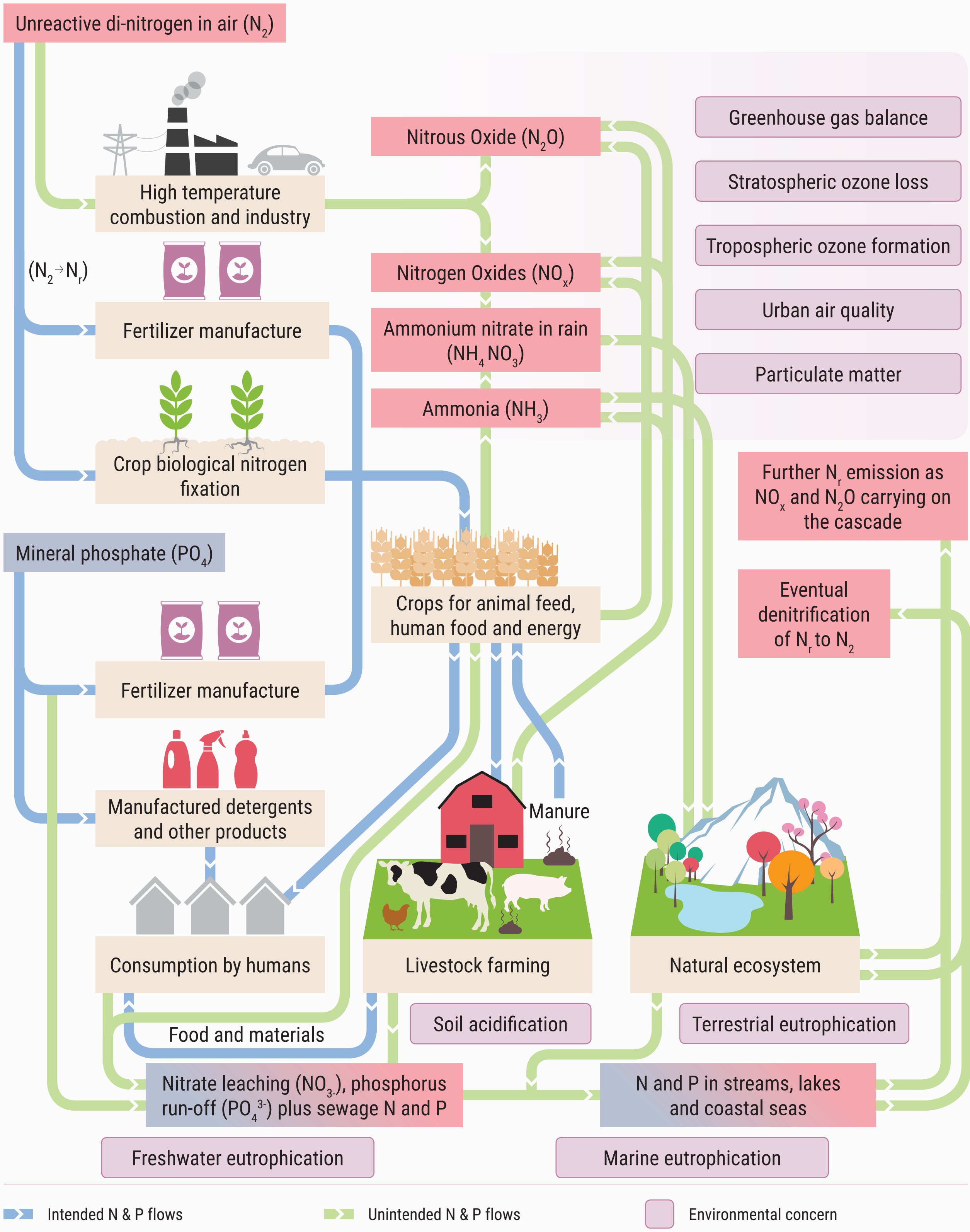
When inorganic or organic N, P and K are applied to crops, some of the edible plant parts are consumed by humans and animals, whose waste can be applied to soil to provide nutrients (Figure 7.2-2). Care should be taken to use waste that is safe for this purpose (see below).

There have been concerns about the long-term availability of phosphorus, as phosphate rock resources are finite (Li, B., Bicknell and Renwick 2019; Alewell *et al*. 2020; Bennett 2020). However, a recent report the United States Geological Survey concluded that phosphate rock shortages are not imminent. World resources of phosphate rock are estimated to be more than 300 billion tons(United States Geological Survey [USGS] 2020).

More nutrients are currently lost than recycled. According to a review of the literature by Schneider *et al*. (2019), studies have estimated that phosphorus from animal and human sources could potentially meet a large proportion of crop requirements. In the EU only 5 per cent of organic waste materials are recycled and used as fertilizer (UNEP 2019). Nevertheless, a substantial share of sewage sludge (biosolids) produced in some countries is used as fertilizer (Figure 7.2-3) (Christodoulou and Stamatelatou 2016; Rutgersson *et al*. 2020).

The use of untreated or contaminated organic inputs could present environmental and human health risks (see Chapter 9, e.g., for the potential effects of pathogens and endocrine disrupters in organic inputs on human health [Chapter 9.2.2] and the potential effects of endocrine disrupters in organic inputs on soil invertebrates [Chapter 9.3.2]). Moreover, the nutrients in such inputs may not match plant nutrient requirements. It has been estimated that recycling all the excreta produced in Sweden in 2017 could have met up to 75 per cent of crop nitrogen and 81 per cent of phosphorus needs, but would have exceeded crop potassium needs by 67 per cent (Akram *et al*. 2019).

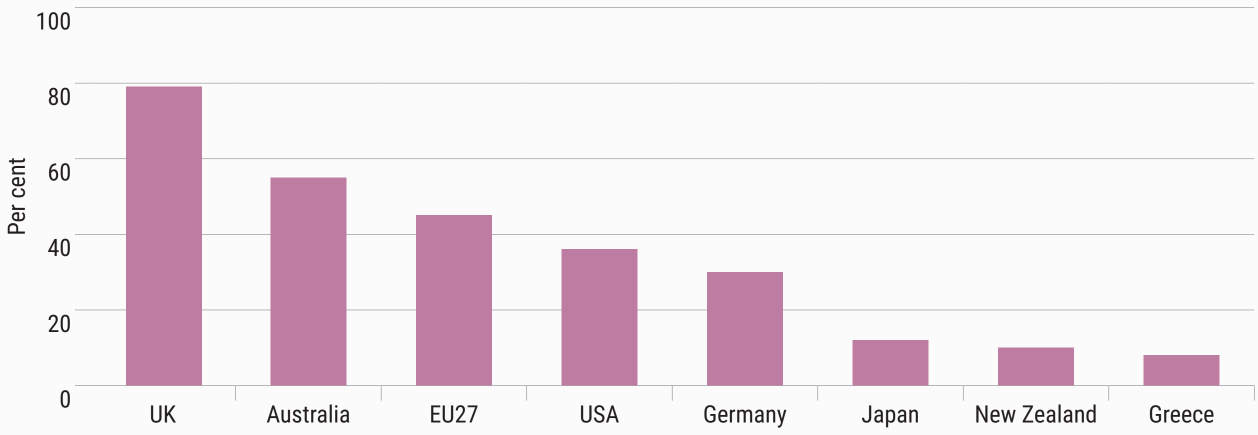
Figure 7.2-2 Simplified overview of nitrogen and phosphorus flows highlighting major anthropogenic sources, and the associated environmental concerns. Sutton *et al.* (2013).



N_r= Reactive Nitrogen and NO_x = Collective reference term for nitric oxide (NO) and nitrogen dioxide (NO_2).

Figure 7.2-3 Percentage of biosolids produced nationally used in agriculture in developed countries.

Christodoulou and Stamatelatou (2016).



7.2.6 The 4Rs of nutrient management

Use by farmers of the 4R nutrient stewardship (4RNS) approach – the right nutrient source, the right application rate, the right time and the right place – is key to minimizing nutrient losses. This approach is applied, for example, in precision agriculture and is a component of integrated soil fertility management (Chapter 7.5.1). A recent development is a global 4RNS framework which embeds the 4Rs in a cropping system and landscape that support the environmental, economic and social dimensions of sustainability (Fixen 2020).

Nutrient sources

Fertilizers should match crop needs and soil properties (Johnson and Bruulsema 2014). Balanced nutrition ensures maximum benefits. Factors influencing the choice of fertilizers include their form (e.g., dry granular products, fluids, straight vs. blends) and their availability (Johnson and Bruulsema 2014).

Application rates

In general, the rate at which fertilizers are applied should meet crop needs, maintain soil fertility, and not exceed plant requirements (to avoid wastage and pollution) (Mutegi, Kiwia and Zingore 2019).

Application rates are specific to each site and cropping system. They are estimated based on the crop's nutrient requirements, the capacity of the soil to supply nutrients, the target yield, the attainable yield under local climatic conditions, fertilizer cost, and the value of the crop products (Fairhurst 2012). Environmental pollution resulting from fertilizer use should also be considered. Determining application rates that meet farmers' needs, ensure profitability for the fertilizer industry and reduce agricultural pollution can be challenging (Kanter, Zhang and Mauzerall 2014).

Nutrient placement

Fertilizers should be applied where crops can use them (Mutegi, Kiwia and Zingore 2019). Methods of fertilizer application for both inorganic and organic fertilizers, and for fertilizers in solid, liquid or gaseous form, include applying the fertilizer to soil by broadcasting or top dressing; applying it in the same furrow or hole as the seed at planting; applying it on the soil surface or in subsoil, either in the same row as seeds or between seed rows; spot application; and deep placement and side dressing (Nkebiwe *et al*. 2016).

Applying fertilizer close to a seed or plant increases plant uptake and, in the case of nitrogen, reduces the risk of volatilization. However, some fertilizers damage the seed or plant if they are placed too close to it. Broadcasting requires less investment in labour and equipment than placing fertilizer close to a seed or plant.

For example, deep placement of fertilizer briquets (e.g., in irrigated rice) demands more labour than the traditional practice of broadcasting (Pasandaran *et al*. 1999). On the other hand, using applicators for deep placement can reduce labour requirements (Wohab *et al*. 2017).

Water soluble fertilizers may be dissolved and applied in the form of foliar sprays, fertigation (e.g., via drip irrigation) or injection into soil. Plants sometimes respond better to application of liquid fertilizers than to that of granular ones. Soil application of liquid inorganic sources of phosphorus, nitrogen and zinc has been shown to produce significantly more grain than application of granular inorganic fertilizers in wheat grown on calcareous soil (Holloway *et al*. 2001).

Foliar application of zinc and iron has been reported to increase concentrations of these micronutrients in harvested grain (Melash *et al*. 2019). The concentration of zinc in wheat almost doubled with foliar application of zinc, but no noticeable change was observed with soil application (Cakman and Kutman 2018). In a review of selenium fertilization strategies, foliar application tended to have more positive responses than soil application for selenium while residual effects lasted longer in the case of soil-applied selenium (Ros *et al*. 2016). Foliar application is more beneficial than soil fertilization when plant demand for nutrients exceeds the roots' capacity to absorb nutrients or soil conditions limit plant uptake of nutrients (Oosterhuis 2009). In a study on vegetables, nitrogen leaching was less in the case of drip irrigation than in that of flooding irrigation (Lv *et al*. 2018). In a study on maize, fertilizer use efficiency was greater with drip irrigation than under rain-fed conditions (Wu, Xu *et al*. 2019). Fertigation allows matching nutrient application with crop demand, as well as better distribution of nutrients in the root zone (Kafkafi and Tachitzky 2011).

Aerial spraying is another method of applying inorganic and organic fertilizers in either solid or liquid form. This method allows application over large areas in a short time. However, it is expensive, requires care to avoid contamination of open waters (Roy *et al*. 2006), and results in losses through volatilization.

Timing of applications

Fertilizers should be available when a crop needs them (Mutegi, Kiwia and Zingore 2019). Basal ("starter") fertilizer, mostly containing N, P and K, is applied at planting or during early stages of plant growth; N fertilizers are also applied during later stages of crop growth as top dressing (Fairhurst 2012). Some crops may not require nitrogen at the early stages of plant growth. In direct seeded rice, for example, basal nitrogen was not necessary until the fourth leaf stage (Chen *et al*. 2018).

Matching nutrient supply with crop requirements improves use efficiency. Basal fertilizers tend to have minimal amounts of nitrogen in order to minimize nitrogen losses, which are more likely when plant roots are small or non-existent than when the roots are well established and nitrogen uptake is high.

7.2.7 Fertilizer storage

Inorganic fertilizers

Fertilizer quality may decline during storage. Some inorganic granulated fertilizers can absorb moisture during storage, making application difficult. Ammonium nitrate and urea are more hygroscopic than most other fertilizers (i.e., they take up moisture from their surroundings more readily) (Albadarin, Lewis and Walker 2017). Such fertilizers should be stored under dry conditions.

Organic fertilizers

Proper storage of organic fertilizers is necessary to minimize nutrient losses and, subsequently, environmental pollution. A global meta-analysis of measures to reduce ammonia emissions from agricultural systems (Ti *et al*. 2019) reported that manure storage management could reduce ammonia emissions by 70-82 per cent. Storage methods that contribute to a reduction of nutrient losses include stacking and compressing manure heaps and protecting manure from wind, water and sunlight, for example, by storing it in a structure with an impermeable floor, a roof and manure covering (Teenestra *et al*. 2015; Ndambi *et al*. 2019).

Poor storage conditions can contribute to an increased risk of fire (e.g., for composts) or the growth of fungi. Accidental explosions of compost being treated have been reported (Miyake 2006). Increased water content can stimulate the development of fungi in stored organic fertilizers (Kasprzycka *et al*. 2018).

7.2.8 Hazard classification and fertilizer compatibility

Based on the literature search conducted for this report, little information on hazard classification or the compatibility of fertilizer materials is available for organic fertilizers.

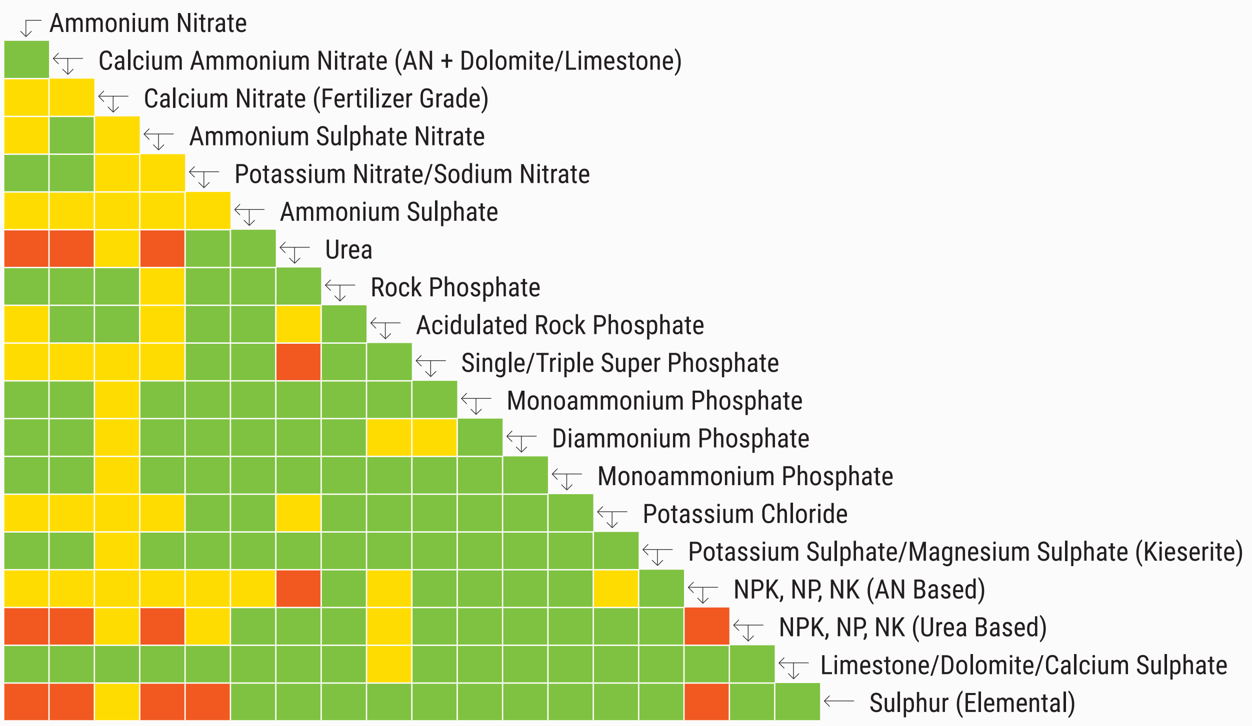
Hazard classification

Ammonium nitrate based fertilizers are thermally stable under normal conditions, but external heat can initiate their decomposition and, for example, cause detonation and the release of toxic gases (European Fertilizer Manufacturers Association [EFMA] 2007). Guidelines exist for the transport, storage and management of such fertilizers (see Table 7.1 for examples).

Regulation EC 2003/2003 of the European Parliament and the Council states that "ammonium nitrate fertilizers of high nitrogen content should conform to certain characteristics to ensure that they are harmless. Manufacturers should ensure that all high nitrogen content ammonium nitrate fertilisers have passed a test of resistance to detonation before those fertilizers are placed on the market" (EU 2003, p. L 304/2).

Under the International Maritime Dangerous Goods (IMDG) code (International Maritime Organization 2019), copper granulates, manganese sulphate, zinc sulphate monohydrate, and blends containing 2 per cent copper granules, 1 per cent manganese sulphate granular or 1 per cent zinc sulphate monohydrate are classified as marine pollutants (see, for example, the Kenya Bureau of Standards code of practice for blending fertilizers; Kenya Bureau of Standards 2014).

Figure 7.2-4 Compatibility of various fertilizer materials. Adapted from Fertilizers Europe (2006).



	Ammonium Nitrate	Calcium Ammonium Nitrate (AN + Dolomite/Limestone)	Calcium Nitrate (Fertilizer Grade)	Ammonium Sulphate Nitrate	Potassium Nitrate/Sodium Nitrate	Ammonium Sulphate	Urea	Rock Phosphate	Acidulated Rock Phosphate	Single/Triple Super Phosphate	Monoammonium Phosphate	Diammonium Phosphate	Monoammonium Phosphate	Potassium Chloride	Potassium Sulphate/Magnesium Sulphate (Kieserite)	NPK, NP, NK (AN Based)	NPK, NP, NK (Urea Based)	Limestone/Dolomite/Calcium Sulphate
Calcium Ammonium Nitrate (AN + Dolomite/Limestone)	🟩																	
Calcium Nitrate (Fertilizer Grade)	🟨	🟨																
Ammonium Sulphate Nitrate	🟨	🟩	🟨															
Potassium Nitrate/Sodium Nitrate	🟩	🟩	🟨	🟨														
Ammonium Sulphate	🟨	🟨	🟨	🟨	🟨													
Urea	🟥	🟥	🟨	🟥	🟩	🟩												
Rock Phosphate	🟩	🟩	🟩	🟨	🟩	🟩	🟩											
Acidulated Rock Phosphate	🟨	🟩	🟩	🟨	🟩	🟩	🟨	🟩										
Single/Triple Super Phosphate	🟨	🟨	🟨	🟨	🟩	🟩	🟥	🟩	🟩									
Monoammonium Phosphate	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩								
Diammonium Phosphate	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟩							
Monoammonium Phosphate	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩						
Potassium Chloride	🟨	🟨	🟨	🟨	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩					
Potassium Sulphate/Magnesium Sulphate (Kieserite)	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩				
NPK, NP, NK (AN Based)	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟩	🟨	🟩	🟩	🟩	🟩	🟨	🟩			
NPK, NP, NK (Urea Based)	🟥	🟥	🟨	🟥	🟨	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟥		
Limestone/Dolomite/Calcium Sulphate	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
Sulphur (Elemental)	🟥	🟥	🟨	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩

🟩 Compatible

🟨 Limited compatibility (chemically, physically and/or safety based)

🟥 Not compatible (chemically, physically and/or safety based)

Table 7.1 Classification of inorganic fertilizers for transportation, storage and handling. European Fertilizer Manufacturers Association (EFMA) (2004); EFMA (2007); Fertilizers Europe (2006); Fertilizers Europe (2007); United States Environmental Protection Agency (US EPA) (2015).

Fertilizers	Hazard description
Sea transport classification	
Type A: Straight N fertilizers containing ammonium nitrate (AN) >80% and dolomite, limestone and/or calcium carbonate ($CaCO_3$); straight N fertilizers containing AN >70% and other inorganic substances not covered above; compound fertilizers containing AN >70%; straight N fertilizers containing AN and ammonium sulphate (AS) in which 45%<AN<70% and AN+AS>70%	Oxidizers, class 5.1, UN 2067. These fertilizers need to pass the UN resistance to detonation test.
Type B: NPK fertilizers with 45%<AN<70%, with ≤0.4% combustible/organic materials; NPK fertilizers with AN<45%, with unrestricted combustible/organic materials and capable of self-sustaining decomposition	Class 9, UN 2071
Type C:	Non-hazardous
Rail transport classification	
Anhydrous ammonia: NH_3	Gas, toxic and corrosive substance (class 2, hazard identification number 268)
Ammonia solution: relative density <0.880 at 15°C in water, with >50% ammonia	Gas, toxic and corrosive substance (class 2, hazard identification number 268)
Ammonia solution: relative density <0.880 at 15°C in water, with >35% but not ≤ 50% ammonia	Toxic gas (class 2, hazard ID 20)
Ammonia solution: relative density 0.880-0.957 at 15°C in water, with >10% but ≤35% ammonia	(class 8, hazard ID 80)
Storage, handling and transportation classification	
Ammonium sulphate: no specific danger known	Not classified as hazardous
Urea:	Not detonable or inflammable
Potassium nitrate: KNO_3	Oxidizer, class 5.1, UN 1486
Sodium nitrate: $NaNO_3$	Oxidizer, class 5.1, UN 1498
Magnesium nitrate: $Mg(NO_3)_2$ or MgN_2O_6	Oxidizer, class 5.1, UN 1474
Calcium nitrate: $Ca(NO_3)_2$	Oxidizer, class 5.1, UN 1454

Some organic inputs, too, are considered potentially dangerous during transportation (International Maritime Organization 2006). For example, seed cake, the residue that remains after oil is extracted from oil-bearing seeds and is mainly used as animal feed or fertilizer, should be substantially free from flammable solvent and properly aged before shipment (BMT n.d).

Compatibility of fertilizer materials

Although most fertilizer materials are compatible when they are blended, some have limited compatibility or are incompatible (Figure 7.2-4). For example, ammonium nitrate and ammonium sulphate are incompatible as this mixture is potentially detonable (Fertilizers Europe 2006).

7.3 Fertilizer demand, sales and use

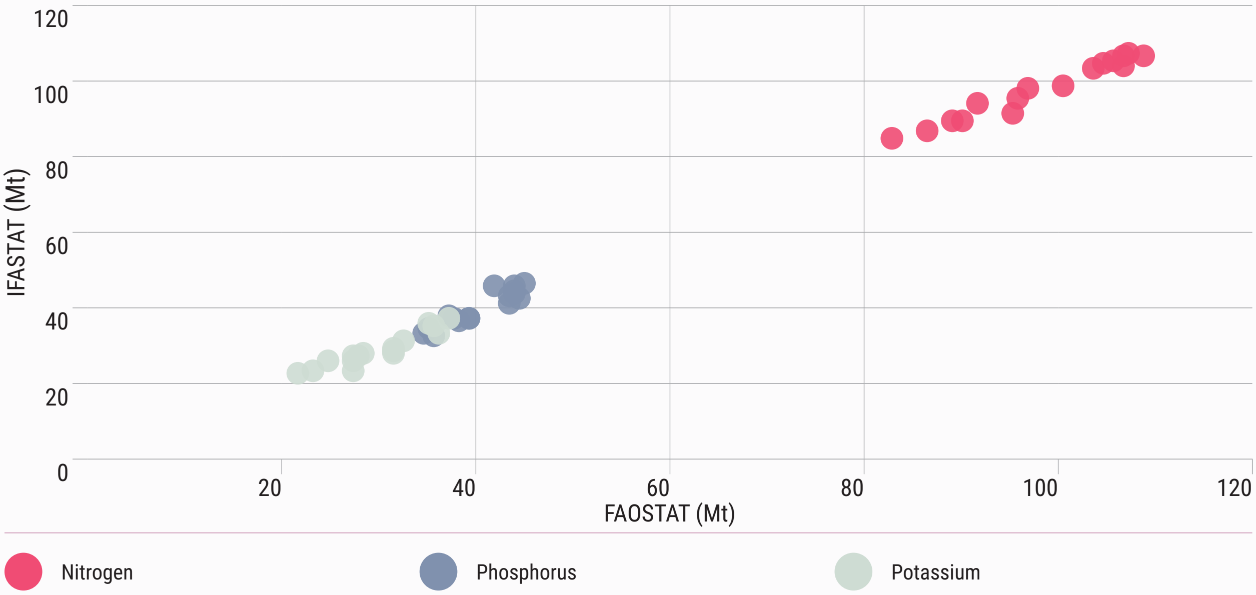
Key fertilizer data sources are the Food and Agriculture Organization of the United Nations (FAO) and the International Fertilizer Association (IFA). FAO data are collected directly from countries as part of official reporting to FAO and disseminated in the FAOSTAT database. IFA data are collected from national fertilizer industry correspondents and disseminated in the Association's IFASTAT database. For the purposes of this analysis, where the focus is largely on global and regional trends for the three main macronutrients, FAO and IFA data are fairly comparable (Figure 7.3-1).

The fertilizer data in FAOSTAT, at the time of this report cover years up to 2018. FAO's most recent *World Fertilizer Trends and Outlook* report covers the period 2017-2022 (FAO 2019b). Similar recent reports by IFA cover 2019-2023 (IFA 2019a; IFA 2019b) and 2020-2024 (IFA 2020a; IFA 2020b). The FAO report was developed by the Fertilizer Outlook Expert Group, comprising representatives of the FAO, IFA, the Fertilizer Association of India (FAI), the International Fertilizer Development Center (IFDC) and The Fertilizer Institute (TFI). IFA outlook reports are developed by IFA with input from the IFA Agriculture Committee and IFA members. The present report uses the FAO database for statistics up to 2018. It uses FAO (2019b), IFA (2019a and 2019b), and IFA (2020a and 2020b) for projections.

This section focuses mainly on inorganic fertilizers, for which considerable data are available. Some estimates for organic fertilizers are also included, but the only publicly available data on quantities are for nitrogen from animal manure (based on statistics concerning animal stocks and the application of the Guidelines of the Intergovernmental Panel on Climate Change [IPCC]) (FAO 2020b). Regional data for Europe include some countries in Eastern Europe and Central Asia (EECA), such as the Russian Federation and Belarus. Data for Latin America include countries in South and Central America and the Caribbean.

The quantities of nitrogen, phosphorus and potassium presented in this report are for elemental nitrogen (N), phosphorus pentoxide

Figure 7.3-1 Comparison of FAOSTAT and IFASTAT data on fertilizer use in agriculture for the period 2002- 2017. IFA (n.d.); FAO (2020a).



Note: the points indicate different years, and values are in million tonnes (Mt)

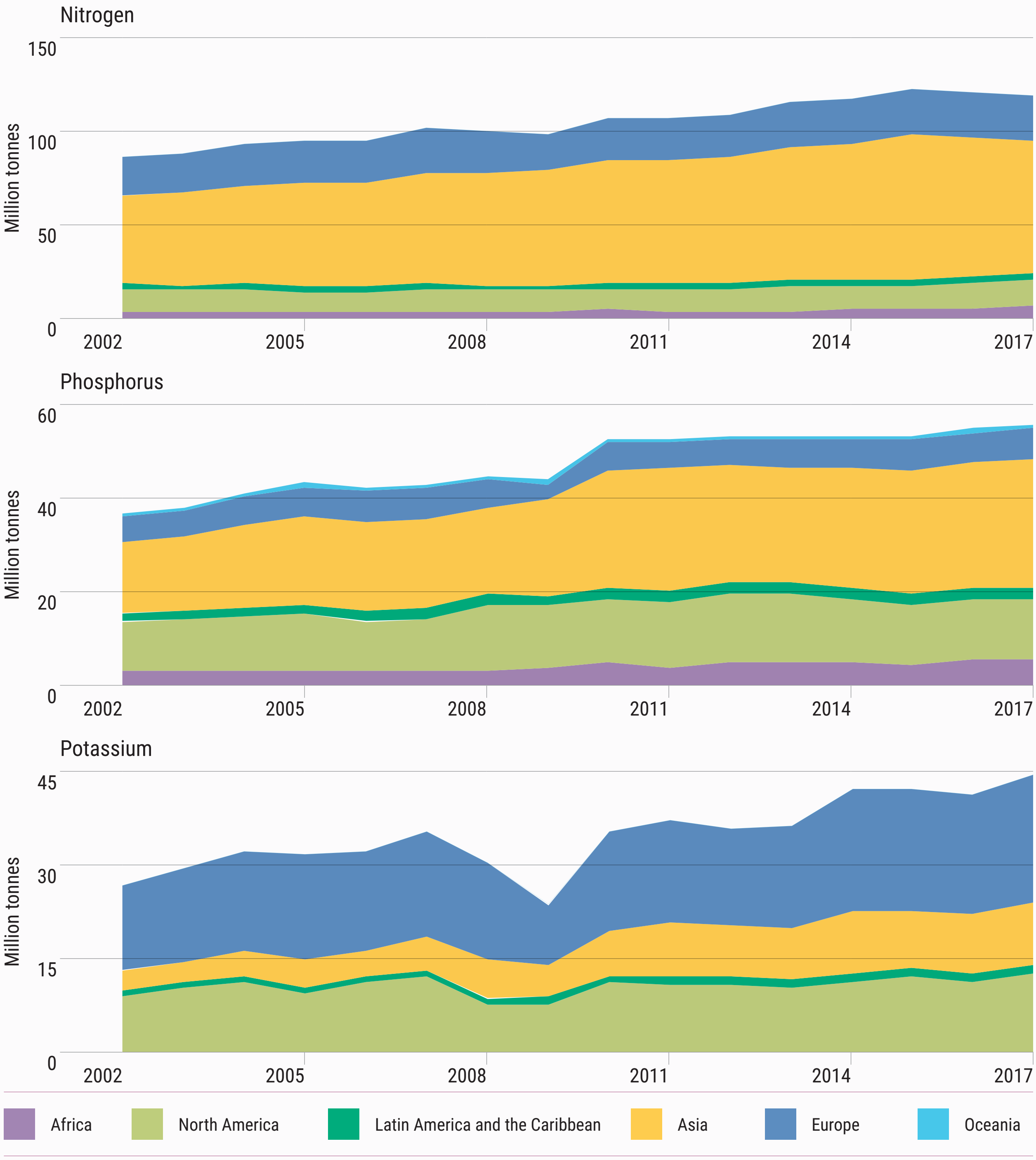
(P_2O_5) and potassium oxide (K_2O). Phosphoric acid (H_3PO_4) is an intermediate product in liquid form used in the manufacture of a wide variety of fertilizers and chemical products (IFA 2020c), the amount of phosphorus in the acid is expressed as P_2O_5. Potassium is also commonly referred to as potash (CropLife 2017; IFA 2020d). As such, the quantities of phosphoric acid and potash presented are for P_2O_5 and K_2O, respectively.

7.3.1 Fertilizer production and supply (current and projected)

Inorganic fertilizer

For the production data from FAO presented below, "production data represent the tonnes of nutrients manufactured into fertilizer products" (FAO 2020c). On the other hand supply data includes not only

Figure 7.3-2 Fertilizer production (Mt). FAO (2020a).



finished products used for plant nutrition, but also finished products used for animal feed and for industrial uses, intermediate products and fertilizer raw materials (IFA 2020e). Supply refers to “the capability or maximum achievable production (potential), derived by multiplying capacity by the highest achievable operating rate” (IFA 2019b).

Between 2002 and 2018 it is estimated that global inorganic fertilizer production increased from 87 to 120 million tons (Mt) for nitrogen, 34 to 44 Mt for phosphorus, and 27 to 45 Mt for potassium. Total production of the three nutrients is estimated to have increased from about 150 to 210 Mt (FAO 2020a) (Figure 7.3-2).

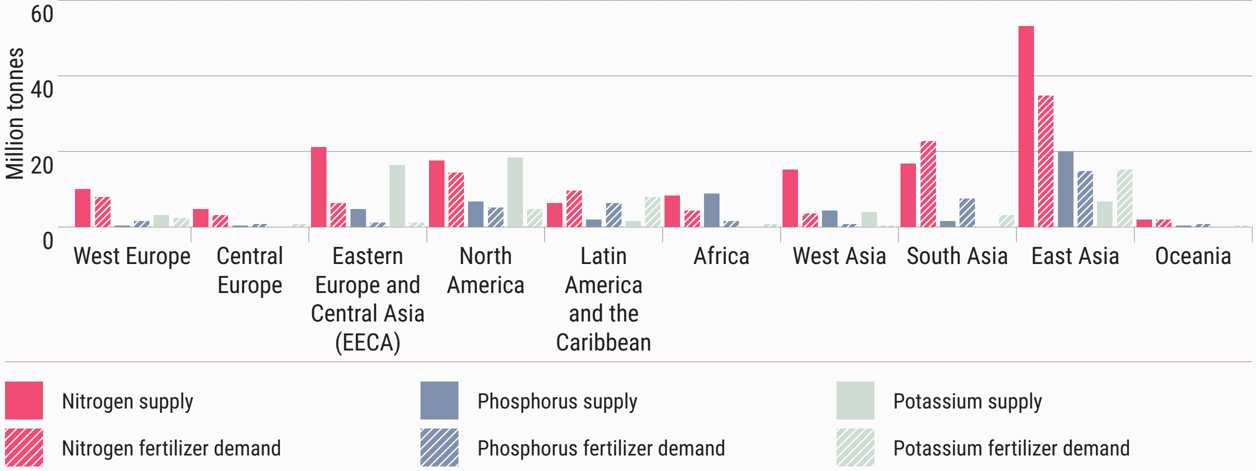
The FAO trends and outlook report and the IFA outlook report for 2019-2023 projected that global supply of ammonia in 2019 would be about 162 Mt and 155 Mt of N respectively, while both reports projected the supply of P_2O_5 and K_2O would be about 50 Mt each (FAO 2019b, IFA 2019b). Both the FAO and IFA reports projected a global nitrogen supply of about 162-163 Mt by 2022. They also projected that the supply of phosphorus and potassium (supplied as phosphoric acid and potash), would be about 52 Mt and 54 Mt, respectively, in 2022.

In general, Asia is the world’s largest supplier of nitrogen and phosphorus; North America and EECA are the largest potassium suppliers (Figure 7.3-3). In China nitrogen production was about 41 Mt in 2015, but fell to 33 Mt in 2018 (FAO 2020a). Nitrogen production is expected to decline further in China between 2019 and 2023 because of continued capacity restructuring, and to increase in EECA, Latin America, Africa and India due to new capacity (IFA 2019b). During the same period phosphorus production is expected to increase in Africa, West Asia, Latin America and South Asia while potassium production is expected to increase in EECA, Canada and China (IFA 2019b).

Organic fertilizer, organo-mineral and biostimulant markets

Inorganic fertilizer is estimated to represent 80 per cent of the total market value of the EU fertilizer industry, with organic fertilizer representing around 5 per cent and organo-mineral fertilizer and biostimulants each representing about 2 per cent (EC 2016; Fertilizers Europe 2019). The economic value of biostimulants in the EU was estimated at between 200 and 400 million euros by the European Biostimulants Industry Council, according to Xu and Gellen (2018).

Figure 7.3-3 Estimated supply and fertilizer demand for nitrogen, phosphorus and potassium in 2019 (Mt).
IFA (2019b).



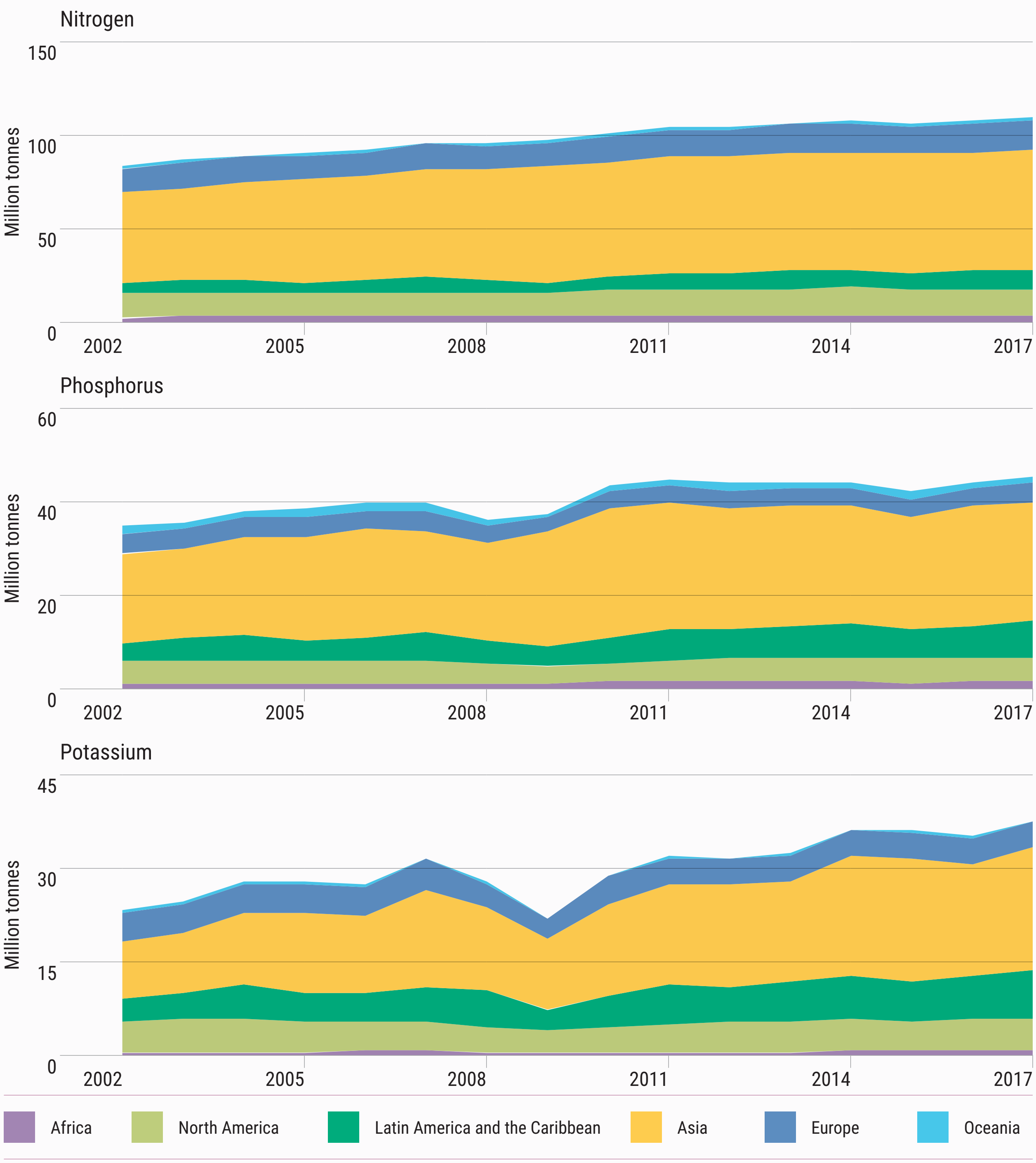
Note: Data for supply of phosphorus and potassium refers to P_2O_5 and K_2O from phosphoric acid and potash, respectively.

7.3.2 Fertilizer demand: N from inorganic fertilizer and manure, P and K from inorganic fertilizer

In this chapter “fertilizer demand” refers to fertilizer use in agriculture. Most of the fertilizer produced in the world is used for agricultural purposes (crop/plant production). For example, according to FAO data for 2018 the nitrogen, phosphorus and potassium used in agriculture were approximately 91, 92 and 87 per cent of the total amount produced in that year, respectively (FAO 2020a).

Between 2002 and 2018 the total amount of nutrients from inorganic fertilizer (nitrogen, phosphorus and potassium) used for agricultural

Figure 7.3-4 Nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) fertilizer use in agriculture (Mt), 2002-2017. FAO (2020a).



purposes globally increased from 140 Mt to 190 Mt of nutrients (FAO 2020a) and the amount of inorganic fertilizer used per hectare increased by about 23 per cent for nitrogen, 13 per cent for phosphorus and 56 per cent for potassium (FAO 2020e). Asia is the largest consumer of nitrogen, phosphorus and potassium from inorganic fertilizers, while Oceania and Africa consume the least (FAO 2020a) (Figure 7.3-4). Latin America is expected to be the main contributor to global growth in the medium term and Africa is expected to be the fastest growing market (International Fertilizer Association [IFA] 2021a). Between 2019 and 2022 agricultural demand for nitrogen was projected to increase from 107 Mt to 112 Mt, that for phosphorus from 47 Mt to 49 Mt, and that for potassium from 38 Mt to 40 Mt, according to the FAO trends and outlook report for 2017-2022. In 2025/2026 global demand for inorganic fertilizer is forecast by the to reach 208.3 Mt nutrients, compared with 198.2 MT in 2020/2021, with Latin America expected to be the main contributor to global growth in the medium term and Africa expected to be the fastest growing market (IFA 2020a; IFA 2020b; IFA 2021a).

Comparison of FAO estimates of the amount of nitrogen in manure left on pastures and in manure applied to the soil (based on statistics on animal stocks and Intergovernmental Panel on Climate Change [IPCC] conversion factors) with the amount of nitrogen used from inorganic fertilizers (based on data provided by countries) suggests that globally about 50 per cent of nitrogen supplied to the soil is from animal manure left on pastures and applied to soil annually(FAO 2020a; FAO 2020b). In general, the amount of nitrogen from manure left in pastures could be about three times the amount of nitrogen from manure applied to soil (Figure 7.3-5) (FAO 2020b). However, it should be noted that use of manure involves the transfer of nutrients across landscapes, while the nitrogen in inorganic fertilizers is a "new input" derived from the Haber-Bosch process which converts atmospheric nitrogen to ammonia by combining nitrogen with hydrogen (Erisman *et al*. 2008).

Figure 7.3-5 Amount of nitrogen (N) excreted in manure which was left in pastures and applied to soil (Mt) (a) between 1961 and 2017, globally, and (b) in different regions (averages for 2003-2017). FAO (2020b).

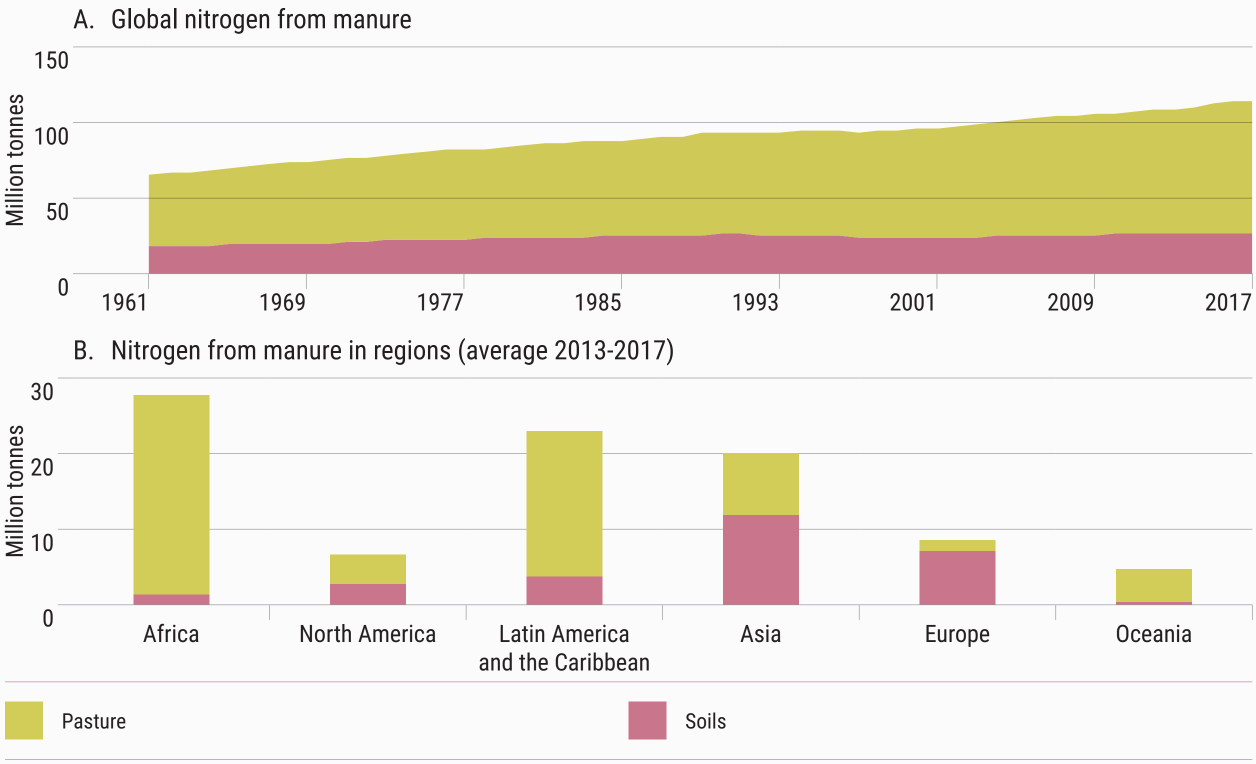
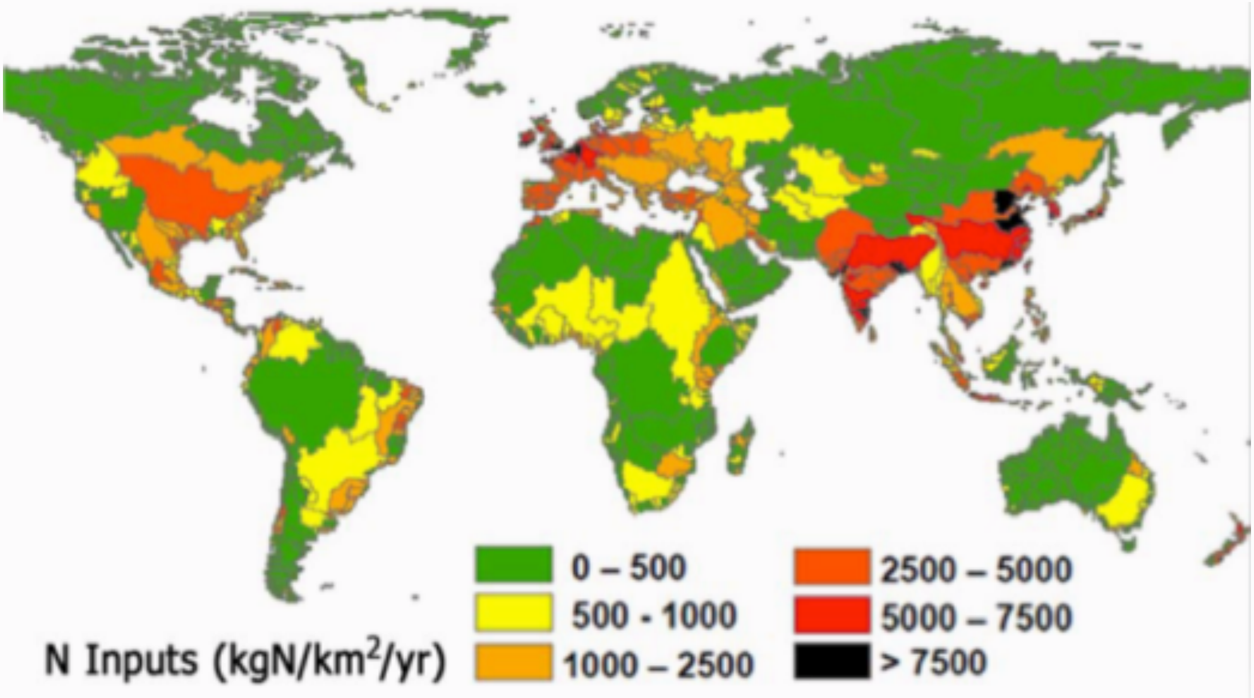


Figure 7.3-6 Estimated net anthropogenic N inputs in the world's main river catchments (1 km2=100 ha).



Estimates of the amounts of phosphorus and potassium supplied by animal manure globally are lacking. However, estimations of the nutrient composition of animal manure reported in the literature. Fairhurst (2012) suggest that it could also contribute substantial amounts of phosphorus and potassium to soils. Animal manure has been estimated to contribute approximately 55 per cent of phosphorus supplied by fertilizers in 2000 (Bouwman *et al*. 2013). According to a phosphorus flow chart showing global phosphorus flows for 2009 by Koppelaar and Weikard (2013), presented in Smits and Woltjer (2018), cropland and pasture may receive more phosphorus from animal manure (about 28 million tons) and other organic sources (7 million tons, mainly from crop loss, residues, food waste and human excreta) than from inorganic fertilizers (about 17 million tons). At the same time, it should be remembered that a proportion of nutrients in manure is or could originally be from inorganic sources.

The leading countries in terms of agricultural consumption of inorganic fertilizer are Brazil, China, India and the United States. About 25 per cent of nitrogen, phosphorus and potassium inorganic fertilizer produced in the world was used in agricultural production in China in 2016 (FAO 2020a). In 2017 the countries with the largest areas of cropland, in declining order, were India, the United States, China, the Russian Federation and Brazil (FAO 2020d). In the same year, among countries with more than 0.5 million ha of cropland, those with the highest rate of nitrogen from inorganic fertilizers compared to their area of cropland included Egypt (342 kg N/ha), China (219 kg N/ha), the Netherlands (209 kg N/ha), Belgium (198 kg N/ha) and the United Kingdom (170 kg N/ha) (FAO 2020d; FAO 2020e)[2].

The amount of manure N applied to cropland was estimated by dividing FAOSTAT data on "total amount of N in the manure applied to soils in a country" (FAO 2020b) by "area under cropland in a country" (FAO 2020d). Among countries with at least 0.5 million ha of cropland, those with the resulting highest rates of nitrogen from

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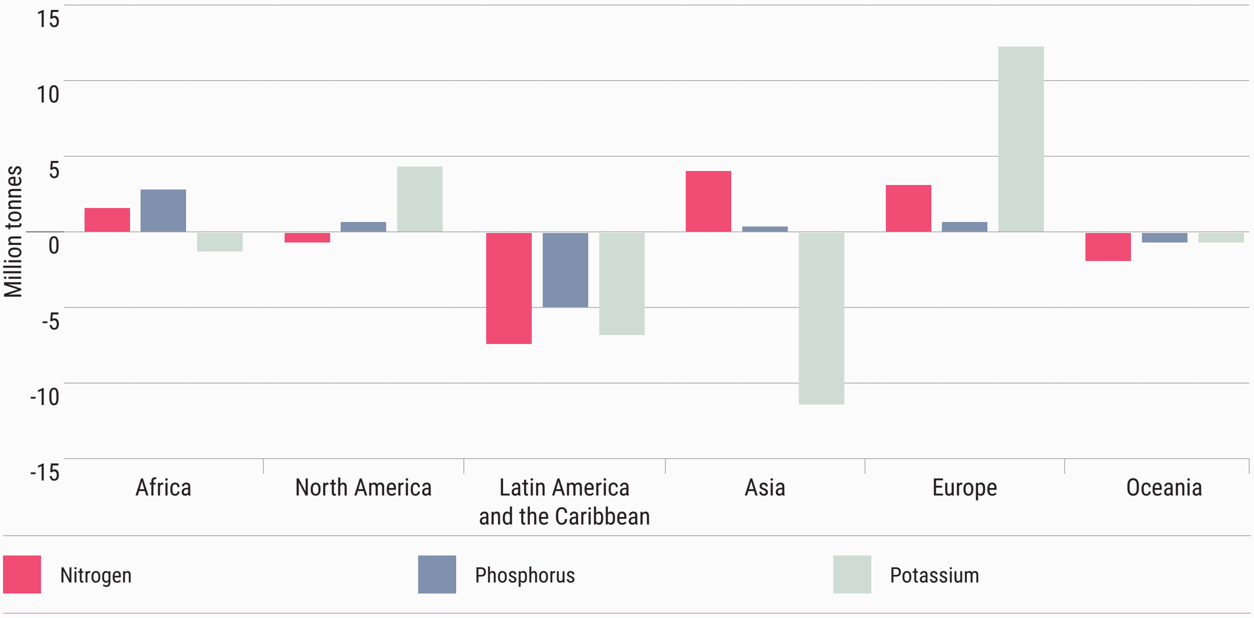
[2] The cut-off of 0.5 million ha of cropland is an arbitrary value used to identify countries with the potential to make substantial contributions to global pollution from nitrogen use.

Figure 7.3-7 Fertilizer exports minus imports, for nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O), in 2017 (Mt). FAO (2020a).



manure were the Netherlands (284 kg/ha), Belgium (161 kg/ha), New Zealand (126 kg/ha), Mongolia (122 kg/ha) and the United Kingdom (83 kg/ha).

Estimates of the amount of nitrogen, summed up for both inorganic and organic fertilizers, applied to soil was least in sub-Saharan countries (less than 50 kg/ha/year applied in many countries). Nitrogen inputs from anthropogenic sources are estimated to be highest in Europe, North America, parts of South and East Asia, and Latin America (Sutton *et al*. 2013) (Figure 7.3-6).

7.3.3 Fertilizer exports and imports

Between 2014 and 2016 the leading net exporting regions were Asia and Europe (including the EECA countries) for nitrogen, Africa for phosphorus, and Europe (including the EECA countries) and North America for potassium (Figure 7.3-7). The leading net importing regions were Latin America and the Caribbean (LAC) for nitrogen and phosphorus and Asia and LAC for potassium.

Global sales revenues for inorganic fertilizers in 2018 were reported to be about USD 151 billion; the global fertilizer market has been projected to grow at a compound annual growth rate (CAGR) of 3.8% in the period 2020-2025 (Mordor Intelligence 2020, as cited by Ilinova, Dmitrieva and Kraslawski 2021) and at a CAGR of 2.1 per cent between 2021 and 2026 (Mordor Intelligence 2021b).

There is not much information available on trade in organic fertilizers. However, indications are that the contribution of organic fertilizers to the fertilizer market is relatively small. For example, it was estimated that global sales of organic fertilizers would be about USD 6.52 billion by the end of 2019 (Bloomberg Business 2019). According to this Bloomberg Business report, the EU represents a large proportion of the global organic fertilizer market (estimated to be about 38 per cent in 2019).

7.4 Fertilizer distribution and sales mechanisms

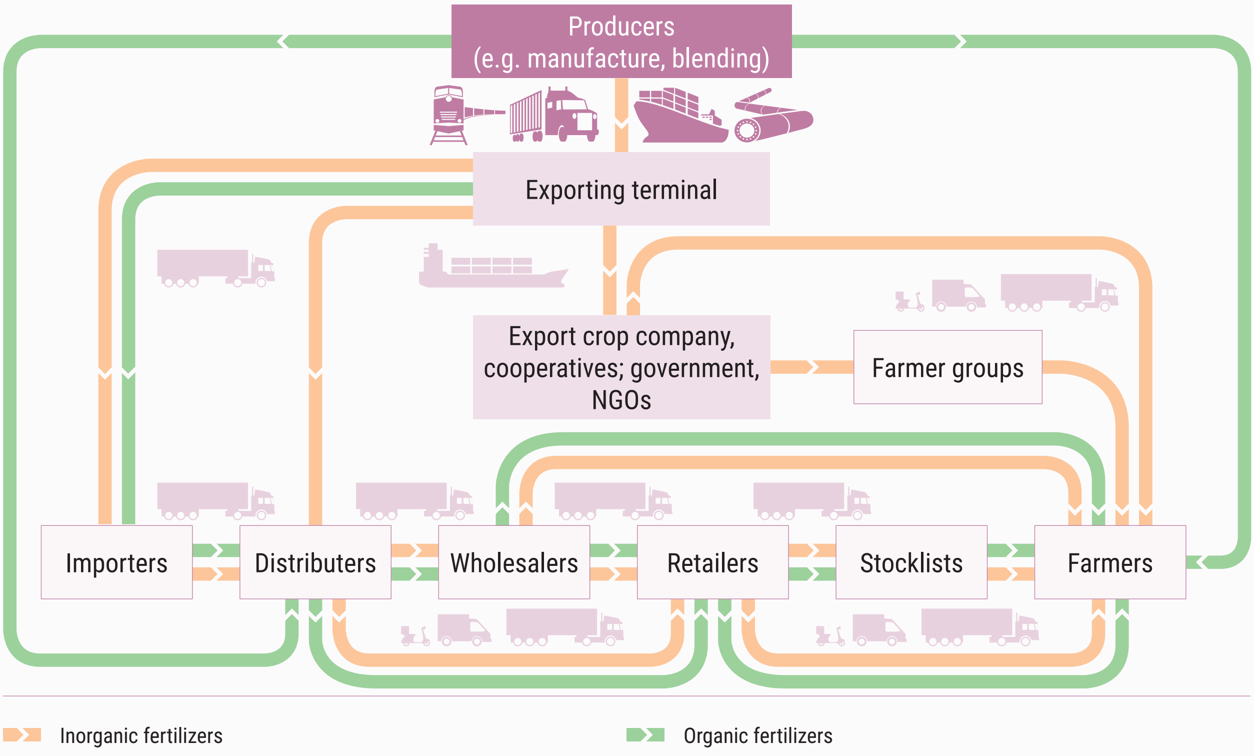
7.4.1 Distribution and marketing

In general, the organic fertilizer supply chain can be shorter than that of inorganic fertilizers, for example where farmers recycle products generated on their own farms or purchase products such as manure from neighbouring farmers.

The fertilizer distribution chain starts with manufacturers/producers (global, regional or national), followed by importers which operate at regional or national level, wholesalers and retailers which operate at national level, and finally farmers who are the fertilizer end users (Figure 7.4-1). Importing can be carried out by private sector importers or government ministries (Hernandez *et al*. 2018). The supply chain can be simple. For example, cooperatives purchase fertilizers to be used by members (e.g., on export crops like tea and coffee) from fertilizer producers (AfricaFertilizer 2012). Governments can purchase fertilizers from producers and importers for distribution to farmers (Hernandez *et al*. 2018).

In high income countries fertilizers are often distributed in bulk or in large bags (500-1,000 kg). In low income countries importers often bag fertilizers before they are transported to distributers. Sometimes the fertilizers are repackaged into smaller quantities and information about them is provided through retailers or stocklists. In Africa some fertilizer producers have blending plants or are investing substantially in building such plants (Diallo *et al*. 2019). Blending plants produce customized fertilizers adapted to local conditions and requirements (Tsujimoto *et al*. 2019). The popularity of blends, which are cheaper to produce than compound fertilizers, has been increasing in sub-Saharan Africa (Mutegi, Kiwia and Zingore 2019).

Figure 7.4-1 Simplified diagram of the fertilizer supply chain. The orange and green lines represent inorganic and organic fertilizers, respectively. AfricaFertlizer (2012) and Li *et al*. (2013).



7.4.2 Organization of the fertilizer industry

Globally the inorganic fertilizer industry is largely represented by the (IFA 2021b). A few IFA members are also involved in organic and organo-inorganic fertilizer production. IFA members represent different sectors of the fertilizer industry. In 2020 there were over 400 members in 70 countries. At regional level there are organizations such as Fertilizers Europe, the Arab Fertilizer Association (AFA), The Fertilizer Institute (TFI) in the United States, Fertilizer Canada, the Fertilizer Association of India (FAI), the Associação Nacional para Difusão de Adubos (ANDA), Fertilizer Australia, and the West Africa Fertilizer Association.

The organic fertilizer industry does not have a global association. In Europe national associations including Acteurs d'une terre plus verte (Afaïa) and L'Union des industries de la fertilisation (UNIFA) in France, BELFORM in Belgium, FOMA in Spain, Assofertilizzanti in Italy and the BMA in the Netherlands cover refined organic fertilizers. The European Consortium of the Organic-Based Fertilizer Industry (ECOFI) provides a representative voice for manufacturers. The lack of a global association for the organic fertilizer industry could be due in part to its traditionally local nature (with regard to both raw materials and markets) and the fact that most producers are small and medium-sized enterprises.

7.4.3 Transportation

Transportation from producers to farmers is mostly carried out by a combination of transport modes, for example by sea from the country of origin to a port close to the importing country, by rail from the port to distributors, and by road from distributers to retailers.

In the United States railroads and waterborne vessels often move fertilizers from a production facility to and throughout the country to warehouses, terminals and retailers (TFI 2016). These forms of transport are especially important for long distance transportation, while roads may be important for short distances, particularly as the product gets closer to farmer customers (TFI 2016). A large share of the fertilizers used in the Corn Belt is shipped on barges on the Mississippi River (TFI 2016; Plume 2019).

In sub-Saharan Africa a large portion of retail costs are for transport, as fertilizer is mostly carried by road within countries and through the continent (Benson and Mogues 2018). According to Gro Intelligence (2016) and Wanzala and Groot (2013), transport costs are a major reason for high fertilizer prices in sub-Saharan Africa. Fertilizer prices there are reported to be the highest in the world, e.g., four times those in Europe (Hernandez and Torero 2018). Data presented in a World Bank report on trade and transport in developing countries (World Bank 2014) suggest that rail transport is cheaper than road transport.

7.4.4 Landlocked countries

Distribution costs tend to be high in landlocked countries, partly due to additional transport costs. For example, in 2007 about 32 per cent of retail prices of fertilizer in landlocked Mali and 22 per cent of those in Tanzania (which has a coastline) were attributed to these costs (Wanzala and Groot 2013). In sub-Saharan Africa the highest urea prices have been reported in three landlocked countries (Cedrez *et al.* 2020). Landlocked countries also have to maintain relatively higher stocks of imported commodities than other countries, incurring greater costs (World Bank 2014).

7.4.5 Commercial sales and subsidies

Subsidies can contribute to a reduction of the quantity of a commercial fertilizer purchased and crowd out the private sector (Mather and Jayne 2018). A major objective of current "smart subsidies" is to boost sustainable development of input markets (Tiba 2011).

Additional information on fertilizer subsidies can be found in Chapter 8.

7.4.6 Fertilizer quality and adulteration

The literature on the status of fertilizer quality and adulteration, published in indexed journals, is minimal or lacking. Hence, the information presented here is based on reports from FAO and IFDC.

A 2011 FAO report stated that 52 per cent of 5,053 fertilizer samples tested in South Asia were substandard (FAO 2011). An assessment study carried out by IFDC in five countries in West Africa in 2010, on samples collected from retailers, found that blends were more likely to be of poor quality than compound fertilizers (12-96 per cent of blended fertilizers vs. 1-16 per cent of compound fertilizers) and that some fertilizers had severe granule degradation. (This report assumed that "agro-dealers", the term used in IFDC reports, were synonymous with "retailers"); poor quality was mainly attributed to uneven distribution of nutrients in bags due to segregation of granules, as well as to poor handling and storage (Sanabria, Dimithe and Algnikou 2013). More recent IFDC studies, on samples taken from retailers shops in Kenya and Tanzania, indicated that some of the fertilizer sold had less nutrient content than indicated on the bags and that some bags could be underweight, although fertilizer was not adulterated (Sanabria *et al*. 2018a; Sanabria *et al*. 2018b).

Information of existing fertilizer regulations and policies is presented in Chapter 8.

7.4.7 Cross-border trade

In sub-Saharan Africa cross-border trade of fertilizer is limited by poor infrastructure, weak economic integration, and delays in crossing borders due to inefficient custom procedures and document requirements (United Nations Economic Commission for Africa and African Development Bank [UNECA and AfDB] 2018). Trading fertilizer across borders largely takes place through formal markets, but informal trading also exists (UNECA and AfDB 2018).

7.5 Drivers of fertilizer use

Drivers of fertilizer use exist at farm level or outside the farm. They can be technological (e.g., fertilizer use efficiency), associated with consumers (e.g., demand for food and food choices), or can even be associated with sustainability aims (e.g., environmental policies). Some factors can encourage increased use of fertilizers and others can discourage it, while still others may have either effect depending on the circumstances.

7.5.1 Factors influencing fertilizer usage: examples

Demand for food (in terms of quantity and quality) and income

Global demand for food continues to grow with the increasing population (Bodirsky *et al*. 2015). Unlike in the past, when growth in agricultural production was largely due to increases in the amount of cropped land, expansion of agricultural area is no longer feasible in many regions and higher production is largely due to agricultural intensification. According to FAO data, between 2002 and 2018 the global population increased by about 21 per cent (FAO 2020g) and cereal production increased by 44 per cent, but the total area harvested for cereals increased by only about 10 per cent (FAO 2020f). The use of fertilizers has been a key component of intensification (Cassman 1999). For example, small-scale farmers in Asia and Latin America increased production dramatically through use of improved seed, greater use of inorganic fertilizers, and good management practices (Voortman, Sonneveld and Keyzer 2003).

Fertilizers may improve the quality of the edible crop part (e.g as a biofortification strategy). Selenium (Se) applied to the soil or to crops can improve crop Se levels, thereby contributing to improved nutrition for human beings and animals (Ros *et al*. 2016).

Policies, subsidies and government support

Developing countries in which there are high levels of hunger tend to have the lowest levels of inorganic fertilizer use. For example, according to the World Bank (2019), in 2018 the prevalence of undernourishment (per cent population) averaged 19 per cent and 18 per cent in least developed countries and in SSA, respectively, but was 3 per cent in Europe and North America. Improving farmers' access to and lowering the costs of inputs such as high-quality seeds, fertilizers and pesticides can contribute to achieving Sustainable Development Goal (SDG) 2 (End hunger, achieve food security and improved nutrition, and promote sustainable agriculture) (United Nations Conference on Trade and Development 2018). Agricultural growth in China has been linked to policies that support fertilizer production and use (Li, Y. *et al*. 2013).

Policies that promote recycling and include standards for fertilizers encourage production by the fertilizer industry of quality fertilizer products from waste and manures. For example, the 2019 EU regulation states that "Promoting increased use of recycled nutrients would further aid the development of the circular economy and allow a more resource-efficient general use of nutrients…" (EU 2019, p. L 170/1). Policies that promote a "clean environment" can also encourage nutrient recycling. In a study carried out in four EU countries (Hou *et al*. 2018), pressure from government regulations was perceived as a key factor stimulating manure treatment. However, some countries lack policies that encourage access to high-quality inorganic and organic fertilizers (as discussed in greater detail in Chapter 8) or nutrient recycling.

Input subsidies can contribute to greater use of fertilizers (Holden 2018), as well as to increasing yields and national production (Jayne *et al*. 2018). They may also have drawbacks. In China subsidies contributed to an adequate supply of affordable fertilizer, which in turn led to fertilizer overuse (Li *et al*. 2013. In India, through heavy subsidization the price of urea has been kept low compared with the prices of phosphorus and potassium fertilizers, leading to unbalanced use of nutrients (overuse of nitrogen) and soil and other types of environmental degradation (Huang, Gulati and Gregory 2017). Ndambi *et al*. (2019) have pointed out that subsidization of the cost of synthetic fertilizers in sub-Saharan Africa could discourage use of manure as fertilizer if there are not incentives for manure use.

Soil degradation

Soil degradation involves deterioration of the soil's physical, chemical and biological properties and is a reason for reduced production. Degradation processes include soil erosion, decline of soil organic carbon, compaction, salinization (accumulation of water-soluble salts), sodification (accumulation of sodium), contamination, and loss of soil biodiversity (Louwagie, Gay and Burrell 2009; Govers *et al*. 2013; Bach *et al*. 2020; Baveye *et al*. 2020).

Overuse of inorganic fertilizer can contribute to desertification and land degradation through changes in the chemical properties that cause soil acidification and reduction of soil organism biodiversity, which may further change soil structure through increased soil compaction and decreased water and air retention capacity. Overuse of inorganic and organic fertilizers can also increase chemical accumulation in soil water and affect water cycling. For example, over-application of nitrogen fertilizers can reduce soil pH, resulting in soil degradation (Kopittke *et al*. 2019), and increase greenhouse gas (GHG) emissions. On the other hand, use of low amounts of fertilizers has been partially associated with soil degradation, e.g., in sub-Saharan Africa (Zingore *et al*. 2015).

Judicious use of fertilizers enhances soil organic matter, reduces conversion of natural land to cropland, and minimizes the risks of additional land degradation. Practices addressing soil degradation include use of organic fertilizers, localized fertilizer application, intercropping (e.g., growing both cereals and legumes), conservation agriculture, ridge tillage, contour farming, terracing (Louwagie, Gay and Burrell 2009) and precision conservation (Delgado, Barrera *et al*. 2019; Delgado, Short *et al*. 2019; Delgado, Sassenrath and Mueller 2020).

Several studies have been carried out on the relationship between fertilizers and soil carbon. Organic fertilizers remediate degraded soils by maintaining and enhancing soil organic matter, improving their physical fertility, and supplying nutrients to crops (Medina *et al*. 2015). In a review of organic inputs and fertilizers by Chivenge, Vanlauwe and Six (2011) soil carbon was associated with increased use of organic inputs; yields were high when inorganic fertilizers were used, and highest when organic inputs were used in combination with inorganic fertilizer. A review by Gram *et al*. (2020) reported that increases in soil carbon were only significant in the case of organic inputs and were more pronounced when these inputs were of high quality. Fertilizer use contributes to an increase in biomass, while incorporation of crop residues in the soil can contribute to increased soil carbon (Hijbeek, van Loon and van Ittersum 2019b). The authors of these three publications point out that using a combination of inorganic and organic fertilizers can be beneficial with respect to both yields and soil carbon. Many other authors (e.g., Bharari *et al*. 2017 and Kumari *et al*. 2019) have drawn similar conclusions.

Fertilizer use efficiency

High fertilizer use efficiency is linked to increased yields, which encourages farmers to invest in fertilizers. Nevertheless, Fixen *et al*. (2015) suggests that a substantial proportion of the fertilizer applied to the soil is lost and not taken up by crop.

There are several ways to estimate nutrient use efficiencies (Fixen *et al*. 2015). In this section "nutrient use efficiency" (or "efficiency") refers to the percentage of fertilizer nutrient recovered in the aboveground plant biomass used (i.e., for a nutrient, the amount of nutrient taken up by the fertilized crop minus the amount taken up by the unfertilized crop, divided by the amount of nutrient applied). In cereals the proportion of applied nitrogen taken up by plants in farmers' fields in the first year ranged from 30-50 per cent in one study (Cassman, Dobermann and Walters 2002). According to Fixen *et al*. (2015), efficiencies in well-managed cereal fields are 40-65 per cent for nitrogen, 15-25 per cent for phosphorus and 30-50 per cent for potassium during the first year of application. After the first season or year, some nutrients remain in the soil and can be taken up by crops in subsequent seasons or years. For example, according to Syers, Johnson and Curtin (2008) it is possible that in some cases a relatively large amount of phosphorus from fertilizer (up to 90 per cent) is taken up by crops in the long term. Dobermann and Cassman (2005) estimated that to meet an anticipated 38 per cent increase in global cereal demand by 2025 a 60 per cent increase in nitrogen use on cereals might be required, partly due to large nutrient losses.

Fertilizer use efficiency is improved by using nutrient-saving technologies such as integrated soil fertility management and precision agriculture. For example, in the Netherlands the level of nitrogen applied in recent years has been reduced to the same level as in the 1960s while yields have doubled (Lassaletta *et al*. 2014).

Improving fertilizer use efficiency may not be enough to meet environmental goals. According to a recent study on nitrogen use efficiency (NUE) in the EU-27 (de Vries and Schulte-Uebbing 2020), in some regions protecting surface water quality would require increasing NUE (to about 72 per cent) while maintaining current levels of nitrogen inputs, whereas in other regions it would require increasing NUE and reducing nitrogen inputs.

Integrated soil fertility management and other approaches

Integrated soil fertility management has been defined as a "set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity. All inputs need to be managed following sound agronomic principles" (Vanlauwe *et al*. 2010). Integrated soil fertility can be used to describe the package of technologies and practices that contribute to improved fertilizer use efficiency, soil health and crop productivity.

Nutrient management practices that reduce nutrient losses include using the right nutrient source and applying the fertilizer at the right rate, the right place and the right time (the 4R approach to nutrient stewardship) (The Fertilizer Institute [TFI] 2017; IFA 2020g) (see Chapter 7.2). The 4R approach contributes to improved fertilizer use efficiency. There is a need to optimize fertilizers for crop mixtures and rotations. For example, in cereal-legume systems the cereal can benefit from the residual effects of the legume (Franke *et al*. 2018) and may therefore need less fertilizer nitrogen.

Some technologies are promoted in packages that include fertilizer use. For example, recommendations for some maize varieties include use of inorganic fertilizers to achieve good yields (Nyagnena and Juma 2014). Some countries provide subsidies for inputs. As reported in a review by Hemming *et al*. (2018), farmers in India were offered subsidized agricultural inputs in the form of mini-kits containing seeds for rice, oilseeds and potatoes, fertilizers and pesticides, and farmers in Mozambique were offered voucher subsidies for an improved maize seed and fertilizer package. Agronomic practices also influence crop demand for fertilizers. For example, fertilizer demand can increase with the size of plant populations (Yang and Fang 2015) and placing the fertilizer close to seed, instead of broadcasting, can increase fertilizer uptake and yields (Nkebiwe *et al*. 2016).

Other examples of soil fertility management options include:

- Improving fertilizer use efficiency by growing cover crops, applying nitrogen fertilizer in splits, using slow-release fertilizers, precision agriculture (see below), and site-specific nutrient management (SSNM) options such as the use of leaf colour charts to match nitrogen with crop demand (Fairhurst 2012).

- Nitrogen leaching which can be reduced by growing cover crops (Abdalla *et al*. 2019) and including crops with deeper root systems in rotations (Delgado *et al*. 2007). Incorporating biochar in soil can reduce both N leaching (Feng *et al*. 2019) and N_2O emissions (Li, Y. *et al*. 2018). However, the costs can be prohibitive for farmers, especially in the short term (Spokas *et al*. 2012; Dickinson *et al*. 2015).

- Using liming materials, for example limestone (calcium carbonate, $CaCO_3$), limestone which contains magnesium carbonate ($CaCO_3$ and $MgCO_3$), and gypsum ($CaSO_4 \cdot 2H_2O$). These are often used as soil amendments (also referred to as "soil conditioners") (Fairhurst 2012). When used to correct the pH of acid soils (Fairhurst 2012), these materials can contribute to increased phosphorus recovery (Kisinyo *et al*. 2014). However, they may increase CO_2 releases to the atmosphere from inorganic carbon (Zamanian and Kuzyakov 2019). Gypsum is used to rehabilitate sodic soils, while each of these amendments is used to supply calcium to plants (Fairhurst 2012).

Precision agriculture

Precision agriculture (or precision farming) improves the targeting of nutrients to plant requirements, enabling farmers to make agricultural management decisions that consider fields' heterogeneity (Finger *et al*. 2019). It reduces nutrient losses, hence contributing to greater economic benefits from fertilizers (Bhakta, Phadikar and Majumer 2019). For example, ammonia emissions were less with precision application of organic inputs than with broadcasting (Nicholson *et al*. 2018) and nitrate leaching losses were lower when remote sensing and management zones were used than with traditional practices (Delgado *et al*. 2005). Luther, Swinton and Deynze (2020) found that in the United States objectives other than income were important drivers for the adoption of conservation and precision technologies; for example, farmers who participated in "working lands" environmental stewardship programmes were considered more likely to adopt both cover cropping and precision soil testing.

The types of technologies adopted can differ with the level of operations. On smallholder farms in West Africa, for example, Aune, Coulibaly and Giller (2017) proposed using good quality seeds primed and treated with a mixture of pesticides and fungicides; low doses of inorganic fertilizers; accurate distribution of seeds and fertilizers; and mechanized sowing and weeding. Large-scale farmers are likely to adopt more advanced technologies (Carli, Xhakollari and Tagliaventi 2017). A review of state-of-the-art precision technologies by Bhakta, Phadikar and Majumder (2019) lists global positioning systems (GPS), remote sensing, wireless on-the go sensors and yield monitors among technologies used for data collection; geospatial tools, soft computing and modern software among the technologies used for data analysis; and variable rate fertigation and variable rate pesticides as means of applying variable rates of inputs. These high-end technologies are probably most suitable for large-scale farmers with high financial capacity, but tools that can be used by smallholder farmers also exist (see below).

Decision support tools for fertilizer recommendations

In view of the need to improve fertilizer efficiency and reduce pollution, fertilizer recommendations have increasingly taken spatial and temporal heterogeneity between and within fields into consideration. Approaches for developing fertilizer recommendations and decision support tools have therefore shifted towards cloud-based tools and site-specific nutrient management (SSNM) based on scientific principles (Ahmad and Mahdi 2018).

Tools like the web-based Nutrient Manager for Rice (NMR) (Bado, Dhaman and Mel 2018), the Nutrient Expert (NE) (Rurinda *et al*. 2020), and the Corn N Calculator (CNC) and Adapt-N (Sela *et al*. 2017) have increased the efficiency with which fertilizer recommendations are developed. In comparison with recommendations based on soil tests, for example, the NE approach has been shown to contribute to the improvement of grain yield, nutrient uptake and fertilizer use efficiency (Yang *et al*. 2017). Sela *et al*. (2017) compared the Corn N Calculator (CNC), a static nitrogen recommendation tool, and Adapt-N, a tool that combines soil, crop, and management information with real-time weather data to estimate optimum N application rates for maize. They found that the Adapt-N tool contributed to increased farmer profits and reduced N application rates in comparison with the CNC, which in turn resulted in substantially lower simulated nitrogen losses to the environment.

Use of fertilizer recommendation tools in association with tools for other inputs and practices, for example RIDEV in rice production, enhances fertilizer use efficiency even more. RIDEV can be used to determine optimum timing of nitrogen fertilizer application and the timing of drainage and harvesting (Wopereis *et al*. 2003). More recently, RiceAdvice has been developed for rice production systems in Africa. It is ready for use or being tested in some countries (RiceAdvice 2019). However, as demonstrated by Cotter *et al*. (2020), it may need data for adaptation to new environments. A key characteristic of these tools is their emphasis on splitting nitrogen for reduced N losses to the environment, better yields, and improved fertilizer use efficiency. In a study using wheat as a test crop, Belete *et al*. (2018) showed that by splitting nitrogen into three doses (one-quarter at sowing, one-half at tillering, and the remaining one-quarter at booting) yields and nitrogen recovery could be improved significantly. When the results of such tools are combined with the application of nutrients in accordance with 4R nutrient stewardship, the effectiveness of fertilizer recommendations on crop yields and the reduction of nutrient releases to the environment is increased.

The adoption of some decision support tools could be constrained by their complexity. In Australia, where most farmers learn about nitrogen fertilizer requirements from commercial crop advisers, these advisers preferred simple decision support systems rather than decision support tools requiring detailed inputs and soil characterization (Schwenke *et al*. 2019). Furthermore, accessing and interpreting data can be a challenge (Weersink *et al*. 2018; Trendov, Varas, and Zeng 2019). The existence of suitable open-access databases and access to internet with sufficient bandwidth for transmission of data can contribute to the increased use of such tools (Delgado, Short *et al*. 2019). Their adoption can also be encouraged by the technical capacities of the research teams and end-users (Bado, Dhaman and Mel 2018).

Fertilizer quality

Awareness that fertilizers could be of poor quality may encourage farmers to exceed recommended rates. For example, the perception that the quality of inorganic fertilizers might be inferior to that of organic ones contributed to increased fertilization rates in China (Yang and Fang 2015). In the case of organic fertilizers, uncertainty about nutrient content can be a barrier to use (Case *et al*. 2017)

According to farmers surveyed in Denmark, the most important barriers to the use of animal manure are unpleasant odour for neighbours, uncertainty about nutrient content, and difficulty in planning and use (Case *et al*. 2017). Concerns about transmission of pathogens and the resulting sanitary requirements (e.g., as evidenced by organic fertilizer regulations) can create additional obstacles to use of organic fertilizers. Hence, the availability of processed organic inputs could encourage use of organic fertilizers. Processing has the advantage of providing inputs with reliable nutrient concentrations and reduced concentrations of contaminants. Bulkiness may be a constraint on the use of unprocessed organic fertilizers. Processing can reduce moisture content, thereby encouraging the use of such fertilizers (Mehta *et al*. 2015).

Farm and household characteristics and objectives

Farm and household characteristics that influence intensification include household income, age and gender of the head of the household, household size, farm size, availability and affordability of inputs, access to equipment and knowledge of technologies (Fairhurst 2012), farmers' engagement in off-farm economic activities, contact with agricultural extension services, and experience in agriculture (Ali, Awumi and Danso-Abbeam 2018). In sub-Saharan Africa male-headed households were reported to be more likely to use modern inputs than female-headed households (Sheahan and Barrett 2017); in addition, young farmers were more likely to invest in intensification than old and poor ones (Wairegi *et al*. 2018). Increased farm size has been associated with a decrease in fertilizer application rates (Wu, Xi *et al*. 2018). However, there seems to be little or no evidence directly linking farmer's margins and their willingness to invest in/adopt technologies and practices that improve fertilizer use efficiency.

Supply (availability of inputs, markets included) and infrastructure

Constraints on inorganic fertilizer supply are partially associated with manufacturing, the enabling environment (Ariga *et al*. 2019), importation, distribution and pricing (Mwangi 1996). In sub-Saharan Africa, where fertilizer prices are among the highest in the world, these prices have largely been attributed to poor infrastructure (e.g., ports, roads, distribution networks) (Mwangi 1996).

The costs of inputs increase with greater distance to input markets (Aggrarwal *et al*. 2018), while farm gate prices fall with greater distance to markets for cultivated products. Proximity to markets has been shown to have a significant positive correlation with fertilizer adoption in Brazil (Morello *et al*. 2018).

Inorganic fertilizers may not be available, may not be delivered on time, or may be packaged in large quantities (which can be a constraint for poor farmers) (Mwangi 1996; Dersseh *et al*. 2016). An adequate supply of inorganic fertilizers that match crop recommendations is lacking in some countries (Stewart *et al*. 2020).

Constraints on the supply of organic fertilizers include lack of sufficient amounts, competition between uses (Nhamo, Kintche and Chikoye 2017), and high transport costs due to weight, bulk and distance from the (Akram *et al*. 2019).

According to a mapping study by Powers *et al*. (2019), the intensification of livestock production and high population densities present opportunities for phosphorus recovery. However, use of the recovered nutrients for crop production can be hampered by distances between croplands and livestock production areas, and between croplands and densely populated areas. The authors showed that there are areas where croplands occur next to areas with dense human populations or close to dense animal populations, creating opportunities for phosphorus recycling.

However, there are cases in which the amounts of organic products exceed demand although they are still spread on soils, not because of their value as fertilizer but just in order to get rid of them. For example, in Europe, where there is spatial separation of livestock systems from cropping systems due to intensification, livestock producers have excessive amounts of manure compared with available land (EIP-AGRI 2017). Hence, in some of these areas excess manure and slurries have contributed to significant pollution of water.

Consumer preferences for organic products

Organic agriculture has been defined as "a production system that sustains the health of soils, ecosystems and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic agriculture combines tradition, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved" (IFOAM – Organics International [IFOAM] n.d.a) Organic farmers are encouraged to use organic inputs such as manure and crop residues, and to adopt practices that mitigate environmental pollution (Sustainable Organic Agriculture Action Network 2013).

Products from organic agriculture are sometimes labelled "organic" by a certification body if they have been produced, stored, processed, handled and marketed in accordance with that body's precise technical specifications (standards) (IFOAM n.d. b). The FAO/WHO Codex Alimentarius Commission has produced Codex Alimentarius guidelines for organically produced foods to guide producers and protect consumers (FAO and WHO 2001).

While the production and marketing of organic products are growing, the area of land under organic agriculture remains relatively small. According to survey results based on available data and presented in Willer *et al*. (2020), the market for organic foods is estimated to be worth some USD 105.5 billion per year (having grown from almost nothing in the 1990s) while about 71.5 million ha was estimated to be under organic agriculture in 2018 (FAO 2020d).

Access to finance (credit)

Use of inputs is also influenced by access to credit (Sheahan and Barrett 2017). Credit-constrained farmers are less likely to purchase inorganic fertilizers (McIntosh, Sarris and Papadoupoulos 2013) and more likely to adopt the use of manure (Kassie *et al*. 2015). For farmers in sub-Saharan Africa, credit is attached to strict collateral and high costs, as annual interest rates are around 30 per cent (Ariga *et al*. 2019).

Access to information, social networks, and membership in cooperatives

Training of extension staff and farmers is necessary for increased adoption of new technologies and practices to achieve sustainable nutrient management. Access to information can contribute to either increased or reduced use of fertilizers. For example, in Ethiopia visits to farmers by extension staff were associated with increased use of fertilizer (Tigabu and Gebeyehu 2018) and in China provision of guidance to farmers in the field was associated with reduced use of excessive amounts (Pan *et al*. 2017).

Social networks are useful for exchange of knowledge between farmers, such as on improved farming practices. Social networks, for example being in a group or knowing fertilizer traders, can act as drivers of intensification by improving the flow of information and access to credit, and subsequently adoption of intensification practices (e.g., fertilizer use) (Kassie *et al*. 2015). Farmers are more likely to adopt technologies if other farmers in their social networks have also adopted them. A study by Wang *et al*. (2018) concluded that membership in agricultural cooperatives can encourage farmers to use organic instead of chemical fertilizers. In coffee cooperatives which consolidate coffee from farmers for sale, farmers may be pressured by other members and extension agents to improve the quality of their berries through intensification for better coffee prices (Bennett *et al*. 2016). At the same time, in such cooperatives farmers with better quality coffee are not rewarded, so that some farmers may be unwilling to invest in inputs (e.g., in use of fertilizers).

Information and communications technology (ICT) is increasingly being used to disseminate new information on agriculture. Even in developing countries, transmission of agricultural information through mobile technologies has been associated with increased adoption of recommended practices (Fabregas, Kremer and Schilbach 2019). Some are less likely to own ICT tools due to lack of resources (Gumucio *et al*. 2018). They are also likely to have less access to information about technologies and to extension services (Ragasa 2012).

Climate change

Fertilizer use has been associated with GHG emissions either directly (e.g., through nitrogen fertilization, liming, and methane emissions from cropping and livestock activities) or during production and transportation (see Chapter 9). Furthermore, climate change and extreme weather events will likely increase the potential for nutrient losses through erosion and leaching (Lal *et al*. 2011). On the other hand, the Green Revolution, in which fertilizer played a large part (Pingali 2012), (see Chapter 10).

Climate change can influence fertilizer consumption. Using a model, Rurinda *et al*. (2015) predicted that the yield decline expected due to climate change could be reduced through use of fertilizers, but the response to fertilizers would decline with climate change. According to a review by Olesen and Bindi (2002), climate change may or may not lead to increased demand for fertilizers in agricultural production in Europe. The use of real time nutrient management strategies that respond to variations in climate events can encourage fertilizer use.

Organic fertilizer industry associations

When the inorganic fertilizer supply side at national and regional levels is under an umbrella association, the fertilizer market is strengthened and effective dialogue with governments or with regional governmental organizations in order to promote trade is made possible (Ariga *et al*. 2019). With regard to the organic supply side, where they are mostly absent, the formation of such associations may need intervention from governments.

7.5.2 Reasons for decreased fertilizer use: examples

Health and environmental concerns, including policies and regulations

Global objectives such as those set out in the Sustainable Development Goals (SDGs) (e.g., SDG 3 on Good Health and Wellbeing, SDG 6 on Clean Water and Sanitation, and SDG 14 on Life Below) are a strong indication of intentions to reduce pollution from nutrients and other sources. Many countries have aligned (or are in the process of aligning) their national agendas to the 2030 Agenda for Sustainable Development through actions, policies, laws and programmes (United Nations Environment Programme and Forum for Law, Environment, Development and Governance 2018). For example, enforcement of the EU Nitrates and National Emission Ceilings Directives reduced fertilizer use in Europe (van Grinsven *et al*. 2015). International and regional partnerships can also align their agenda with the United Nations' 2030 Agenda for Sustainable Development. For example, IFA has embarked on developing an Industry code of practice on nutrient stewardship to support implementation of the 2019 *International Code of Conduct for the Sustainable Use and Management of Fertilizers* (FAO 2019a) (Williams 2019).

More information on Conventions and policies influencing (or with the potential to influence) fertilizer use is presented in Chapter 8.

Adoption of approaches and technologies that improve fertilizer use efficiency

Approaches and technologies that improve fertilizer use efficiency (such as the 4R approach) can contribute to reduced fertilizer use. For example, cost saving was one reason given by farmers in the United States for using precision agriculture technology (Thompson *et al*. 2019), which suggests that this technology contributes to reduced use of inputs. In a study on urea deep placement (UDP) technology in Bangladesh, the rate of urea fertilizer application to rice was reduced by about 50 per cent and profitability was higher when UDP technology was used (Rahman and Barmon 2015). In a study in China, reducing nitrogen fertilization rates by about 15-18 per cent combined with enhanced management practices contributed to an increase in yields (by about 11 per cent) as well a reduction of the amount of nitrogen used (by about 1.2 Mt) (Cui *et al*. 2018).

Despite the existence of technologies that improve fertilizer use efficiency, their adoption has not always been successful. For example, the traditional training approach has not contributed to a reduction in the use of nitrogen fertilizers (Huang *et al*. 2015).

Improved varieties (e.g., plant breeding, gene editing)

Yields are higher when nitrogen is applied to improved varieties than to traditional varieties (Hurley, Koo and Tesfaye 2018). The use of organic fertilizer has been positively correlated with growing improved varieties in West Africa (Kpadonou *et al*. 2015). There have been studies on the contribution of gene editing to improved nutrient use by crops (McAllister, Beatty and Good 2012). An example is a study on improving nitrogen use efficiency in barley (Han *et al*. 2016). Future study topics proposed include plant breeding to optimize the benefits of microbial biofertilizers (Trivedi *et al*. 2017). Even where such crops were grown, however, there would be a need to use fertilizers to replace nutrients lost through the removal of plant biomass from fields. Despite their potential benefits, use of these crops could pose environmental risks (Raina *et al*. 2018). The perceived risks have raised concerns among consumers (McFadden and Smyth 2019). Research efforts have sometimes been unbalanced. For example, crop breeding has resulted in high-yield crops while root biomass has remained almost unchanged, e.g., in soybeans (Li, S. *et al*. 2019) and wheat (Junaidi *et al*. 2018).

Crop mixtures and rotations

Legume-based mixed cropping and intercropping/rotation can reduce the need for external inputs of fertilizers/manures. Herridge, Peoples and Boddey (2008) estimated that in 2005 legumes (pulses and oilseeds) fixed about 21 million tons of nitrogen. A review by Crews and Peoples (2004) concluded that obtaining nitrogen from legumes is potentially more sustainable than obtaining it from industrial sources. Biological nitrogen fixation (Figure 7.2-2) by legumes and the incorporation of legume residues in the soil improve soil fertility (Morgan *et al*. 2019). Subsidies have been reported to contribute to increased adoption of legume production. For example, in Malawi the subsidized input package covers legume seeds apart from fertilizer and maize seeds, and farmers who received the subsidy were more likely to grow legumes than other farmers (Koppmair, Kassie and Quaim 2017). Other incentives suggested include policies to make legume production more profitable, a “meat tax” to encourage reduction of meat consumption and encourage consumption of legumes, and a carbon tax that rewards farmers for reducing emissions and for increased soil carbon (Kuhulman, Helming and Linderhof 2017).

Reducing food loss and wastage, dietary choices

About 25 per cent of food produced may be lost along the food chain (Houlton *et al*. 2019). In low income countries more food waste occurs on the farm, for example during storage and transportation, while in high income countries more occurs outside the farm, for example at consumer level. Reducing food losses can make more food available to consumers, contribute to reduced nutrient losses, and reduce the need for fertilizers.

Looking at nutrient pollution from the point of view of the planetary boundaries concept described by Rockström *et al*. (2009), the food system affects several planetary boundaries, including the nitrogen and phosphorus cycles. A modelling study by Springmann *et al*. (2018) which looked at food-related environmental impacts in 2010 and 2050 concluded that keeping within the planetary boundaries associated with the food system requires making dietary changes towards more plant-based diets, improving management practices and technologies, and reducing food loss and waste.

This implies that minimizing the adverse impacts of fertilizers means making changes in the food system, not just in crop and livestock production. Thus, there is a need to include measures that encourage dietary changes and contribute to a more efficient "from-farm-to-fork" food chain in sustainability efforts.

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