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Assessment and monitoring of climatic change impacts on mangrove ecosystems

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PREFACE

The closely-related issues of greenhouse emissions, global warming and climate change have recently come to the top of the international environmental agenda. In particular, concerns over the problems expected to be associated with the potential impacts of climate change have grown over the past decade and captured the attention of the scientific community, the politicians, decision makers, as well as the private and public sectors. These problems may prove to be among the major environmental problems facing the marine environment and adjacent coastal areas in the near future. Therefore, and in line with Decision 14/20 of the Governing Council on "Global Climate Change", the Oceans and Coastal Areas Programme Activity Centre (OCA/PAC) of the United Nations Environment Programme (UNEP) launched and supported a number of activities designed to assess the potential impact of climate change and to assist the Governments concerned in identification and implementation of suitable response measures which may mitigate the negative consequences of the impact.

Since 1987 to date, Task Teams on Implications of Climate Change were established for eleven regions covered by the Regional Seas programme: Mediterranean, Wider Caribbean, South Pacific, East Asian Seas, South Asian Seas, South-East Pacific, Eastern Africa, West and Central Africa, the Kuwait Action Plan region, the Red Sea and Gulf of Aden and the Black Sea. Some of these Regional Task Teams enjoy the support of the Intergovernmental Oceanographic Commission (IOC) of UNESCO and other relevant international, regional and non-governmental organizations. In addition, two Global Task Teams on Expected Impacts of Climate Change on Coral Reefs and on Mangroves were established in cooperation with IOC and UNESCO respectively.

The initial objective of these Task Teams was to prepare regional and global overviews and site-specific case studies on the possible impact of predicted climate change on the ecological systems, as well as on the socio-economic activities and structures, based on the climate change models/scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) and widely accepted by the international scientific community.

These overviews are expected to examine at the regional and global levels the possible effects of the sea-level rise and temperature elevations on the coastal, terrestrial and aquatic ecosystems including deltas, estuaries, wetlands, coastal plains, coral reefs, mangroves, lagoons, etc., and to examine the possible effects of climatic, physiographic and ecological changes on the socio-economic structures and activities, and determine the areas or systems which appear to be most vulnerable to the above effects.

The global overviews were intended to account for the above effects on both the coral reefs and mangroves as important, critical and vulnerable ecosystems.

Following the completion of these regional overviews, and based on their findings, site-specific case studies are developed by the Task Teams for areas identified as most vulnerable and needing urgent attention. The results of these case studies should provide expert advice to the national authorities concerned in defining specific policy options and suitable response measures for the protection and sustainable development of these ecosystems.

The work of the Task Team on Mangroves, organized and supported by UNESCO, was completed in 1993 and was led by Prof. Colin Field, who acted as Coordinator of the Task Team. The present report is largely based on the contributions by the individual members of the Task Team, whose cooperation with the Task Team Coordinator is hereby acknowledged and appreciated (see Foreword).

FOREWORD

In November 1991, COMAR (of UNESCO) invited a panel of 16 experts, on behalf of UNEP/UNESCO, to a preparatory task team meeting to consider "the Impact of Expected Climate Changes on Mangroves", in Bangkok, Thailand. The report of the meeting was published by UNESCO (1992a). Subsequent to this meeting, COMAR created a 14-member UNEP/UNESCO Task Team on the "Impact of Expected Climate Change on Mangroves". UNEP, IOC, and WMO had separately recognized the need to focus studies on mangrove ecosystems related to climate change (IOC, 1991).

The first meeting of the UNEP/UNESCO Task Team was held in Rio de Janeiro 1-3 June 1992, and the results were published by UNEP/UNESCO (1992b). The primary role of the Task Team is to advise on the design, development, and organization of the proposed global monitoring of the effect of climate change on mangroves. The Task Team agreed to undertake three initiatives to support its primary objective. These were:

a)   to carry out a review of the literature and to prepare an overview of some aspects of expected global change on mangrove ecosystems and the probable affects on the exploitation of the system, with the aim of identifying policy options and suitable response measures.

b)   to prepare three specific case studies involving low island, arid coast and deltaic sites. It was considered that these sites would provide a representative range of mangrove habitats and would provide experience of experimental design, data collection and analysis, that would be invaluable for the successful establishment of a long-term mangrove monitoring system.

c)   to prepare a position paper on the theoretical and technical basis for data acquisition, experimental design and the analysis of data, including possible modelling approaches, that could be used for the development of the specific case studies and the long-term monitoring programme concerned with mangrove ecosystems.

It became clear after some initial consideration of the tasks that had to be undertaken that the most coherent approach would be to combine the outcome of initiative (1) and initiative (3) and to present the findings as a consolidated report. An initial draft of the report was prepared by a sub-group of the Task Team, consisting of Björn Kjerfve (Convenor), Donald Macintosh, Barry Clough and Sanga Sabhasri, at a preliminary meeting in Phuket, Thailand.

A Meeting of the Task Team in Okinawa, Japan in July 1993, considered the initial draft report and recommended that it be expanded by the addition of further contributions from members of the Task Team. The final report contains a review of the relevant literature, some policy options and the recommended criteria for selecting mangrove monitoring and study sites. The Task Team also recommended that the report be published by UNEP

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Chairman
UNEP-UNESCO Task Team on the Impact of Expected
Climate Change on Mangroves

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1. EXECUTIVE SUMMARY

As mangroves are one of the most prominent coastal ecosystems in tropical and many subtropical areas around the world, it is likely that the impact by climate change on mangroves will have greater economic and social significance, when compared to the effect of climate change on most other coastal ecosystems. Mangrove ecosystems consist largely of trees with life spans of the order of several decades, so that long-term climate change may be gauged by structural and functional responses of mangrove communities. Other tropical and subtropical coastal ecosystems, such as salt marshes and seagrass beds, exhibit more pronounced short-term variability because of seasonal and interannual fluctuations, and turn over too quickly to be useful for gauging climatic change.

The uncertainty and variability of climate change is still much debated and far from universally accepted. The purpose of this report is not to argue whether global climatic change is occurring, but rather to assess the expected type and magnitude of impacts on mangrove ecosystems, if and when global climate change does occur. Coastal ecosystems, including mangroves, are especially vulnerable because of economic and social pressures in addition to their location at land-sea margins.

Mangrove ecosystems cover approximately 15 million hectares globally, with 6.9 million hectares in the Indo-Pacific Region, 4.1 million hectares in South and Central America and the Caribbean, and 3.5 million hectares in Africa. The important communities of plants, animals, and microbes found in mangrove ecosystems are described in the report.

Throughout the world, mangroves have considerable environmental and ecological values as well as providing significant socio-economic benefits to national and local economies and local communities. Mangrove ecosystems, because of their location, are expected to be amongst the first ecosystems to be affected by any global climatic change, in particular from the effects of increasing sea level and changes in wind, wave, current, and storm patterns.

The Intergovernmental Panel on Climate Change (IPCC) scenarios for climate change have been used here as the basis for projecting future trends regarding climate change on mangrove ecosystems and they are presented in Table 4 of the report.

Major responses by mangrove ecosystems to predicted climate changes are estimated as follows:

a)   Rise in global mean sea level

It is estimated that the global mean sea level will rise by 6.0 cm per decade as a result of global warming. It is difficult to estimate the changes in local relative sea level. It is expected that:

- Mangrove communities will progress landward if accretion of sediment is sufficient or unless constrained by topography.

- Erosion along the seaward margins of mangrove systems will increase.

- Rate of sea-level rise will determine whether mangroves can re-establish.

- Secondary productivity per unit area will probably increase due to greater availability of nutrients due to erosion.

b)   Increase in atmospheric CO_2 concentration.

It is estimated that the atmospheric level of CO_2 will increase by 0.5% per year. It is expected that:

- Mangrove canopy photosynthesis will not be significantly increased.

- The water use efficiency of mangroves will be enhanced; this may or may not be reflected in enhanced growth.

■   Not all species will respond similarly.

c)   Increase in atmospheric temperature

It is estimated that global mean temperature will rise by 0.3°C per decade. However, changes in the tropics may not be as great and there will be less difference between the seasons. It is expected that:

■   A number of mangrove species will migrate towards higher latitudes.

■   There will be changes in the phenological patterns of reproduction and growth in many mangrove species.

■   Overall net and gross productivity of mangrove ecosystems will increase.

■   Plant and animal biodiversity in mangroves will increase and plant and animal composition will change.

■   Mangrove microbial processes will accelerate.

d)   Changes in precipitation patterns

It is predicted that the patterns of precipitation will change but that they are likely to vary regionally and locally without a fixed global pattern. It is also predicted that the incidence of heavy rainfall will increase and the incidence of light rainfall will decrease. It is expected that:

■   Changes in soil water content and soil salinity will have a significant impact on the growth of mangroves.

■   An increase in the precipitation to evapotranspiration ratio will result in an increased rate of primary production by mangroves.

■   An increase in soil salinity will reduce the primary productivity and growth of mangroves.

■   Mangrove animals that are euryhaline will be largely unaffected by increases in salinity but the distribution of stenohaline species will be altered significantly.

Impacts of climate change on landuse, utilization and exploitation of mangroves are expected as:

■   Increased risk of flooding of low lying areas.

■   Increased erosion of vulnerable soft coast.

■   Increased risk of saline intrusion.

■   Increased frequency of damage from storm surges.

The following policy options need to be considered:

a)   Coastal protection

Maintenance of existing protective barriers may need to be relocated landward. Consideration should be given to the establishment or extension of a mangrove green belts to provide a natural barrier for coastal protection. It would be useful to develop guidelines and procedures for the afforestation of suitable coastal areas with mangroves and to train local people to have the necessary skills.

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b)   Agriculture

Agricultural activities are likely to be affected by salt water intrusion. This may necessitate the construction of protective barriers or the relocation of the agricultural activities. In planning future agricultural activities landuse planners should take into account the likely economic life span of the development.

c)   Aquaculture

Aquacultural activities will require modification of management practices. In time, ponds may have to be located in more landward areas. A protective barrier of mangroves should be established and maintained to the seaward of aquaculture ponds. Coastal aquacultural investments will be highly susceptible to alterations in the environmental conditions of the mangroves and the environment should be closely monitored for early indications of change.

d)   Forestry

Forestry activities will be affected by changes in the phenology of reproduction and growth, changes in aridity, changes in salinity and direct disruption of specific sites by sea-level rise and storms. Forest managers should closely monitor the environment of the forest for early indications of change.

It is almost impossible to identify the response of mangrove ecosystems to single factors such as temperature or sea-level rise. Rather, mangrove ecosystems are likely to exhibit synergistic responses to a combination of changing climate parameters, making the analysis of cause and effect difficult. Also, the complexity and scale of responses will be highly site specific.

It must also be stressed that the man-induced climate changes are far from certain. Equally, the effects of climate change on mangroves are uncertain. It must be appreciated that changes to mangrove ecosystems are just as likely to be caused by natural events or the impact of the activities of man. It is therefore important that governments establish base line data on their coast lines and mangrove ecosystems so that any changes that may occur, for what ever reason, will be detected at an early stage.

A study and monitoring programme to assess the impact of climate change on mangrove ecosystems should be implemented.

As climate change effects might be most pronounced in those places where mangrove ecosystems are close to the extremes of their latitudinal distribution it is also recommended that examples of such sites be included in the monitoring programme. It will be easier to detect change in systems that are currently relatively stable. In order to narrow the scope of studies to reasonable proportions, at least three representative types of mangrove ecosystem should be examined: (a) well developed deltaic sites, (b) sites along arid coasts, and (c) low island sites.

A long-term monitoring and study programme should be designed that can be implemented at a small number of primary sites for long-term and intensive studies and well-designed experiments. Additional secondary sites should be selected for the gathering of complementary information and intermittent or routine studies and experiments, covering a wide geographical distribution of sites and types.

To achieve optimal use of resources, primary sites should be mangrove sites, which already are well documented and have relevant information and time series data available, such as meteorological and tidal records, species composition, geomorphology, and sea-level change. A full list of parameters to be measured is provided in the report. At each selected primary site, a parallel training programme should be enacted to provide protocols with respect to acquisition, analysis, and interpretation of data. This will encourage the sustainability of long term acquisition of accurate field data and their local use. The training programme will provide the site-based technical personnel with the necessary knowledge to execute monitoring activities and studies and interpret the results.

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Secondary sites should be selected for additional monitoring and study activities to complement the primary sites, and to provide comparable local information globally. The degree of implementation of any programme activity at secondary sites would ultimately depend on the availability of funds and resources.

It is important to organize a reliable network for mangrove monitoring and study activities for a long-term duration, at least several decades. The resulting long-term data would not only serve to assess the impact of climate change on mangroves, but also serve short-term local needs to aid in management of coastal environments. An integral part of any monitoring and study must include the design of experiments, modelling exercises, and systematic analysis and interpretation of all data on an on-going basis. It is stressed that modifications to mangrove ecosystems due to climatic change may be very difficult to discern from modifications due to anthropogenic actions and episodic natural events. Experiments should be designed carefully with consideration given to such complications.

A list of criteria for selecting suitable mangrove study and monitoring sites is provided in the report. The criteria presented cover eight important categories: (a) physical characteristics, (b) site area, (c) availability of existing site data, (d) government approval and support, (e) institutional and personnel support, (f) data base accessibility, (g) infrastructure, and (h) training and education requirements.

2.   INTRODUCTION

Over the last ten years a great deal has been written about the possible results of man-induced climate change and there is a general acceptance that if man continues to pollute the atmosphere at the present rate there will be significant warming of the earth's atmosphere by the end of the next century, primarily due to an enhanced level of carbon dioxide. There are other predictions that indicate sea-level rise, changes in precipitation patterns, frequency of tropical storms and changes in ultra-violet light intensities. There is a concerted international effort to monitor changes to the environment that may result from man-induced climate change. The Intergovernmental Oceanographic Commission (IOC) has developed a Global Ocean Observing System (GOOS) that will work closely with other international observing bodies and national agencies.

Initially GOOS has identified five modules that it will concentrate on:

a)   monitoring of the coastal zone environment and its changes.

b)   climate monitoring, assessment and prediction.

c)   marine meteorological and oceanographic operational services.

d)   assessment and prediction of the health of the ocean.

e)   monitoring and assessment of marine living resources.

As part of module (a) a UNEP/UNESCO task team has been formed to advise on the design, development and operation of a proposed pilot monitoring activity of the effects of climate change on mangrove ecosystems.

Mangrove ecosystems have attracted increased scientific attention over the past ten years, partially stimulated by the activities of UNESCO(COMAR) and UNDP in the Pacific, Asia, Africa, South America and the Caribbean. In recent times the International Society for Mangroves Ecosystems has been formed as a non-government organisation based in Okinawa, Japan in an effort to continue to foster international cooperation in the study and management of mangrove ecosystems.

A result of these activities is that mangrove ecosystems have become recognised by many scientists, governments and planners as important and productive ecosystems that must be managed carefully on a sustainable basis. It has also been recognised that in many parts of the world the activities of man have destroyed large areas of mangroves. As mangroves grow in the intertidal zones in tropical and sub-tropical regions it is likely that they will be early indicators of any rise in sea level that may accompany a rise in the temperature of the earth's atmosphere.

This report surveys the scientific literature and estimates how the various components of the mangrove ecosystem may respond to expected climate change. It also considers the impact of climate change on the use of mangroves by man and suggests various policy options that could be used by governments to prepare for the predicted climate change.

The report then goes on to outline several hypotheses that need to be tested to determine whether climate change is occurring and whether such changes are affecting mangrove ecosystems. Finally the report outlines in detail an approach for studying and monitoring changes to mangrove ecosystems on a long term basis.

Mangrove ecosystems are inherently dynamic and they are currently experiencing substantial changes as a result of natural events and man-induced pressures. The possibility of changes in climate further affecting their structure and function is an added complication. The problem is to resolve the effects due to climate change from effects that are being induced by other factors. Such resolution can be achieved only through a very carefully designed monitoring programme carried out over many years.

The predictions for climate change have been impressively documented but they remain predictions and have wide margins for error. The predictions for the effects of climate change on mangrove ecosystems are presented in this report and are also subject to wide margins of error. Combining the two sets of predictions together produces a very uncertain picture that must be viewed with caution. However, it would be unwise to ignore the possibility that low lying coastal regions of the tropics and subtropics may be adversely affected by climate change in the future. It would be sensible for all countries that might be affected to take steps to establish base-line data for their mangrove ecosystems and to monitor them for change. This report gives some indication of the steps that should be taken.

3. MANGROVE ECOSYSTEMS

3.1. EXTENT AND CHARACTERISTICS

Mangrove ecosystems are a conspicuous feature of the coastal zone in tropical and subtropical latitudes. The world-wide distribution of mangroves in shown in Figure 1. These wetland ecosystems include forests, waterways, mudflats, and salt pans. They support salt-tolerant (halophytic) mangrove trees, associated hardwood trees, palms, shrubs, epiphytes (lianas, lichens, ferns, and orchids), algae, fungi, microflora, meiofauna, bacteria, marine and terrestrial animals, birds, insects, finfish, and shellfish. Restricted predominantly to the intertidal area between spring tide high and low waters, mangroves are found in river deltas, fronting river-dominated coasts, as borders of estuaries and lagoons, and as patches or fringes in carbonate sediments along small island shores.

Mangrove ecosystems are estimated to cover 15 million hectares worldwide (Lacerda & Diop, 1993). The Indo-Pacific region has 6.9 million hectares of mangrove wetlands, South and Central America together with the Caribbean has 4.1 million hectares, and Africa has 3.5 million hectares (Lacerda & Diop, 1993). They form a coastal fringe vegetation zone between land and sea. Mangroves represent complex wetland ecosystems, which under optimal conditions attain the stature of forests, accommodating trees reaching heights up to 45 m. They are either regularly or occasionally inundated by brackish or marine waters by tidal flushing (IUCN, 1983; Snedaker & Snedaker, 1984; UNDP/UNESCO, 1986; Tomlinson, 1986; Kjerfve, 1990).

Mangroves are inhabited in many places by humans, usually belonging to traditional communities, who harvest fish and other natural resources from the mangrove ecosystem. Mangrove systems are recognized as having important environmental and ecological values as well as providing significant socio-economic benefits to national and local economies (Hamilton & Snedaker, 1984; Dixon, 1989; Lal, 1990; Lugo, 1990). Mangroves are subjected to intense human development in many subtropical and tropical coastal countries, and the area of mangroves is in general decreasing (Ong, 1984) as a result of pond aquaculture operations, agriculture, construction of dikes and roads, and other forms of human encroachment.

3.2 GEOMORPHOLOGY, SEDIMENTS AND BIOGEOCHEMISTRY

Geological morphology, sediment texture, chemistry, deposition and erosional processes, as well as tides, waves and currents, all play a significant role in determining the succession of mangrove species.

3.2.1 Geomorphology

Many authors have drawn attention to the complex biogeomorphological relationships in mangrove communities (Davis, 1940; Thom, 1967; Semeniuk 1980; Woodroffe et al., 1985). Thom (1982, 1984) and Woodroffe (1987) identified nine geomorphic settings in which mangroves occur. For the present purposes, it is sufficient to group these nine settings into three broad types according to the dominant physical processes involved in sediment transport and erosion. These three types are river-dominated, tide-dominated, and marine-dominated (mainly carbonate sediments associated with coral reefs).

1	2	3	4	5	6
W America	E America	W Africa	E Africa	Indo-Malesia	Australasia
Atlantic East Pacific (AEP)			Indo West Pacific (IWP)		
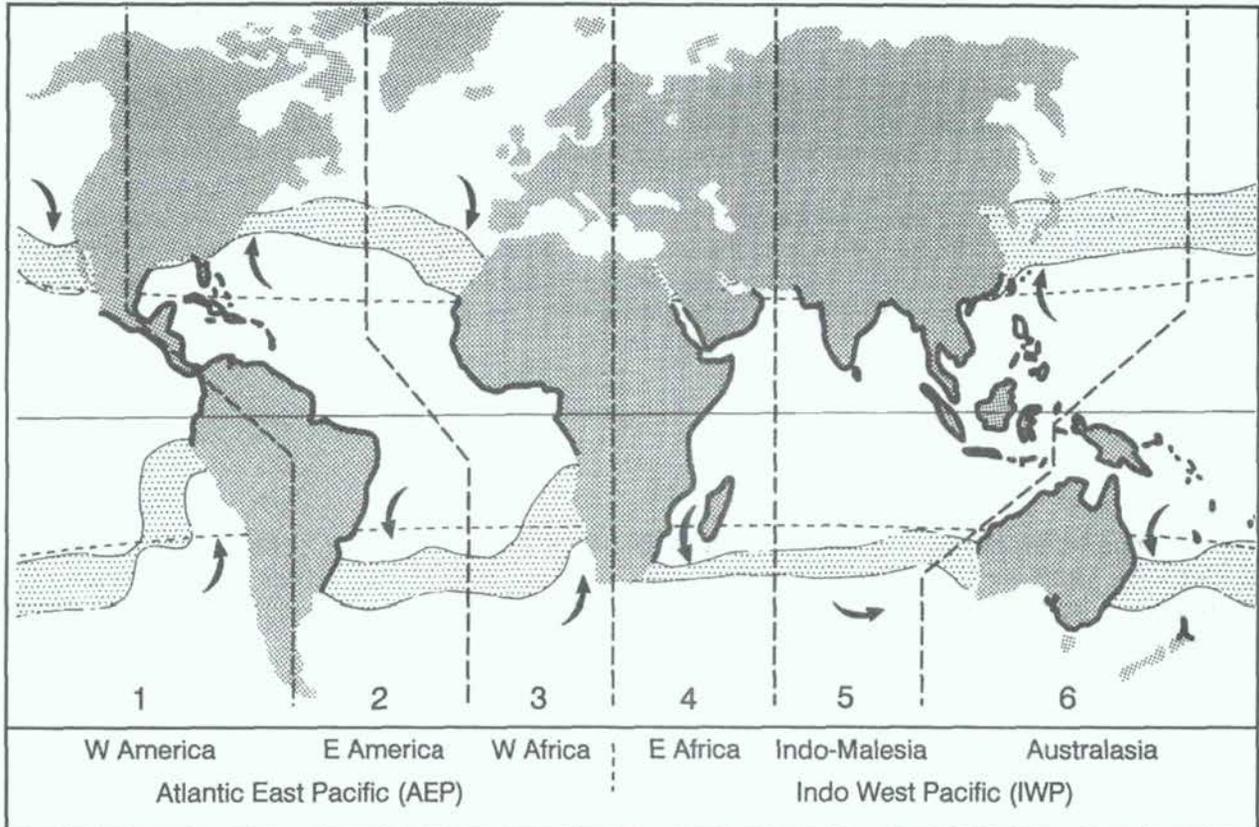
Figure 1: World distribution of mangroves, showing range of 20°C isotherms in January and July, major ocean currents influencing latitudinal range and six biogeographic regions grouped in two global hemispheres. (Duke, 1992)

Thom (1982) attempted to place mangroves into a sea-level framework based on the concepts of constructional and destructional coastal evolution. He noted the great difficult in matching geomorphological and ecological histories. However, he concluded that sea-level fall may lead to strong zoning of species, peat formation and invasion by salt marsh. Conversely, sea-level rise may engender poor zonation and shoreline accumulation of organic debris. He also concluded that mangrove community response to sea-level change is far from predictable. Woodroffe (1990) concluded that for a given climatic tidal environment and a particular pool of mangrove species for a specific region, the history of the land surface and contemporary geomorphic and associated pedogenic processes together determine the pattern of mangrove growth. Mangrove ecosystems may be considered dynamic and there is geological and contemporary evidence (Woodroffe & Grindrod, 1991) that mangrove ecosystems can extend or contract rapidly in response to regional topographical and climatic changes. The ecosystem that is being considered in this review is therefore likely to show significant local changes as a result of natural climatic and geological disturbances and it is also likely to be affected by stresses induced by activities related to uses made by

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man. Such systems will exhibit marked spatial and temporal fluctuations as a result of the influences that have been mentioned.

3.2.2 Mangrove Sedimentation Processes

There is clear evidence from the Holocene record of C^{14} dated mangrove stratigraphy of low rates of accretion in organic low island mangrove peats, and high rates of accretion in more inorganic high island and continental margin mangrove sediments. More recent sedimentation can be studied by use of Cs^{137}, Pb^{210}, artificial sediment markers and inserted stakes. There has been little work of this nature in mangroves, but far more in salt marshes.

Lynch, *et al.* (1989) showed accretion rates of 14 to 17cm/100yrs in an infrequently flooded mangrove basin at Rookery Bay, Florida. At Terminos Lagoon, Mexico, accretion rates at a river dominated mangrove site were an average of 32cm/100yrs and a maximum of 44cm/100yrs while at a tidal dominated site accretion rates were an average of 20cm/100yrs and a minimum of 10cm/100yrs. Like the Holocene record, this study shows how mangroves close to rivers have higher sedimentation rates than those that are tidally dominated.

Table 1

Rates of mangrove peat accretion

Location	Source	Rate of accretion (cm/100 years)
Low Islands		
Tongatapu	Ellison, 1989	7.7
Grand Cayman	Woodroffe, 1981	8.8-9.0
Bermuda	Ellison, 1992	8.5-10.6
High Islands		
Fiji	Latham, 1979	13.1
	Matsushima, *et al.*, 1984	7.6
	Southern, 1986	11.7
Caroline Islands	Bloom, 1970	3.0-25.3
	Matsumoto, *et al.*, 1986	13.7
	Ward, 1988	13.4-14.0
	Miyagi & Fujimoto, 1989	8.5-11.0
Samoa	Bloom, 1980	18.8
	Matsushima, *et al.*, 1984	9.9-10.5
	Ellison, (unpublished)	15.2-40.0
Australia, Hinchinbrook Island		
	Risk & Rhodes, 1985	4.5-10.6
Jamaica	Digerfeldt & Enell, 1984	18.7-27.4

The Holocene record of mangrove stratigraphy shows that mangroves can keep up with slow sea-level rise, and there is variance in this ability according to physiographic location, this dependent on the sediment supply (Ellison & Stoddart, 1991). Table 1 summarises the available stratigraphic work. Low islands have no rivers, so accretion is by accumulation of an organic peat. Studies from three locations show fairly uniform rates of accretion, of 7.7-10.6cm/100yrs. High islands have small catchment rivers that deliver sediment to the coastal zone, and mangrove accretion rates are shown to be higher but variable by location. Continental margins have large catchment rivers, and studies from Australia show extensive progradation under mangroves, even during sea-level rise.

3.2.3 Biogeochemistry

The amount of organic carbon, phosphorous and nitrogen expected from mangrove forests is a very important parameter for assessing the productivity of these systems. In order to understand the system it is necessary to consider the nutrient inputs and outputs and to attempt estimates of the quantitative importance of each. (Boto, 1982; Twilley et al., 1992). It is beyond the scope of this review to consider the large literature on this subject but the possible impact of climate change on biogeochemistry will be considered briefly in a later section.


Figure 2: Rhizophora stylosa. Ha Tinh Province, Vietnam
(Photo D. J. Macintosh).

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3.3.   FLORA IN MANGROVE ECOSYSTEMS

A mangrove is a tree, shrub, palm or ground fern which normally grows above mean sea level in the intertidal zone of marine coastal environments or estuarine margins (Duke, 1992). Mangroves have a combination of morphological and physiological adaptations to cope with their unique habitat. Different taxa have different mechanisms. These may include aerial roots, viviparous propagules, salt glands, and salt exclusion and salt storage strategies. Approximately 59 species of true mangroves are recognised which contribute significantly to the structure of mangrove forests (Table 2). The best developed mangroves grow along humid tropical coasts, here they often form extensive tidal forests with trees of more than 1m in diameter and heights of 20-45m. Mangroves also extend well into temperate regions, but the number of species decreases with increasing latitude (Chapman, 1976; Blasco, 1984; Tomlinson, 1986; Duke, 1992). The present latitudinal limits of mangroves are close to 31°N in southern Japan (Hosokawa *et al.*, 1977), 31°N on Mexico's Pacific coast, 32°N in Bermuda, 32°S in southern Brazil, and 38°S in southern Australia (Wells, 1983). Mangrove communities at these high latitudinal extremes are floristically simple, in each cased comprising only a single species. Duke (1992) points out that mangrove species are divided into two global hemispheres (Figure 1) the Atlantic East Pacific and the Indo West Pacific and that these approximately equal portions of the earth also have roughly equivalent areal extents of mangrove forests. However, the Atlantic East Pacific region has fewer species while the most diverse flora is seen in the Indo West Pacific region. Based on species presence these two primary regions may be divided into six discrete secondary regions as shown in Figure 1. For detailed discussion of the global distribution of mangroves Duke's paper should be consulted.

Table 2

Families, genera, and species of true mangrove trees and shrubs worldwide (adapted from Duke, 1992).

Family	Genus	Species number
Major Families		
Avicenniaceae	*Avicennia*	8
Combretaceae	*Conocarpus*	1
	Laguncularia	1
	Lumnitzera	3
Palmae	*Nypa*	1
Rhizophoraceae	*Bruguiera*	6
	Ceriops	3
	Kandelia	1
	Rhizophora	6
Sonneratiaceae	*Sonneratia*	6
Minor Families		
Acanthaceae	*Acanthus*	2
Bignoniaceae	*Dolichandrone*	1
Bombacaceae	*Camptostemon*	2
Caesalpiniaceae	*Cynometra*	1
Ebenaceae	*Diospyros*	1
Euphorbiaceae	*Excoecaria*	2
Lythracea	*Pemphis*	1
Meliaceae	*Aglaia*	2
	Xylocarpus	1
Myrsinaceae	*Aegiceras*	2
Myrtaceae	*Osbornia*	1
Pellicieraceae	*Pelliciera*	1
Plumbaginaceae	*Aegialitis*	2
Pteridaceae	*Acrosticum*	3
Rubiaceae	*Scyphiphora*	1
Sterculiaceae	*Heriteria*	3

An example of *Rhizophora stylosa* is shown in Figure 2.

Mangroves also occur naturally along arid coastlines, notably the coasts of Pakistan, northern Africa, the Arabian Peninsula, the west coast of Australia, and the northeastern coast of Brazil. Mangrove communities in arid climates are also floristically simple, and usually comprising relatively few species (Zahran, 1977; Kenneally, 1982; Wells, 1983; Ansari, 1986).

The decrease in mangrove and associated species with increasing latitude is generally attributed to the corresponding decrease in sea surface or air temperatures (Saenger et al., 1977; Blasco, 1984; Tomlinson, 1986; Clüsener & Breckle, 1987), whereas the low floristic diversity of arid coasts can be explained at least partly in terms of differences in tolerance to salt, water, and radiation stress between species (Clough et al., 1982; Ball 1988; Ball et al., 1988, Lovelock & Clough, 1992; Lovelock et al., 1992). The minimum water temperature during the winter is the most important factor regulating presence or absence of mangrove species. Temperature, salinity and aridity, as reflected in the precipitation/evapotranspiration ratio (P/ET), appear to be key environmental factors influencing the growth and survival of individual mangrove species along environmental gradients (Blasco, 1984). However, it should be noted that the present distribution of mangrove species may also be related to the direction of prevailing nearshore ocean currents for propagule dispersal.

3.4. FAUNA IN MANGROVE ECOSYSTEMS

Mangrove ecosystems support large populations of animals from many taxa of the animal kingdom, ranging from protozoans to mammals. This diversity is illustrated in the many publications on mangroves describing the distribution and abundance of mangrove macro-fauna (e.g. Berry, 1964; Sasekumar, 1974; Frith et al., 1976; Hutchings & Recher, 1981). In comparison to mangrove plants, however, the mangrove fauna has been poorly studied, with the exception of the most prominent groups, especially the larger crustaceans and molluscs (Warner, 1967; Berry, 1975; Malley, 1977; Houlihan, 1979; Aveline, 1980; Hong & Chin, 1983; Santhakumaran, 1983; Jones, 1984; Macintosh, 1988; Micheli et al., 1991), and more recently, mangrove insects (Murphy, 1990a,b; Macintosh et al., 1991). An example of Scylla serrata, a mangrove crab is shown in Figure 3.

An indication of the numbers of mangrove-associated animals according to taxa is given by IUCN (1983) and summarized in Table 3. Mangroves are the primary habitat of most of these species, even though they also occur in other habitats or migrate into and out of mangrove systems. The resident mangrove fauna also consists of many animal taxa and species, but certain groups show a high level of adaptation to mangrove conditions and tend to dominate numerically. These groups include particularly intertidal crustaceans and molluscs (Malley, 1977; Santhakumaran, 1983; Sigurdsson & Sundari, 1990), various insect families (Murphy, 1990a) and a number of other highly adapted species of diverse origin (Berry, 1972; Milward, 1982).

The distinction between animals which are wholly dependent, permanent residents of mangrove ecosystems, and others which are only opportunist visitors is still debated by zoologists who argue over what constitutes the true fauna of mangroves. However it is important to make this distinction in the context of the impact of climatic change on mangroves because the temporary, or visiting, species have the potential to respond to environmental changes differently to the resident fauna. The logical assumption is that the degree of impact on each animal species resulting from climatic change on mangroves will increase in relation to its degree of dependency on the mangrove ecosystem.

A third faunal group in mangrove ecosystems, about which very little is known, is the soil meiofauna, defined as organisms in the size range from 53 to 1000 um. This poorly studied community consists of many taxa, but nematodes, copepods, and protozoans tend to be most widely distributed and abundant. Numerically, nematodes dominate the meiofauna of intertidal sediments in mangrove systems, constituting from 80% to more than 90% of the meiofauna community (Sasekumar, 1981; Chandrasekhara Rao & Misra, 1983; Hodda & Nicholas, 1985). Meiofaunal densities in mangrove sediments are highest in the surface layer (0-5 cm), but values vary considerably both between locations and at the micro-habitat level.

The few ecological studies reported on the mangrove meiofauna indicate the great importance of this faunal assemblage in the conversion of mangrove primary production to detritus (Subrahmanian et al., 1984) and as a food source for the many mangrove animals which are deposit feeders/detritivores or surface grazers (Sasekumar, 1981). In these roles, the meiofauna are ultimately associated with the

mangrove soil microbial populations. Some of the most abundant intertidal mangrove deposit feeders, including crabs and mangrove mudskippers (Boleophthalmus and Scartelaos spp.), are reported to consume large quantities of meiofauna, as do mangrove associated penaeid shrimps and a number of fish species (Chong, 1977; Sasekumar, 1981). Given the significance of the meiofauna in the detritus-based food web of the mangrove ecosystem, it is clearly important also to try to predict the potential impact of climate change on this productive benthic community.
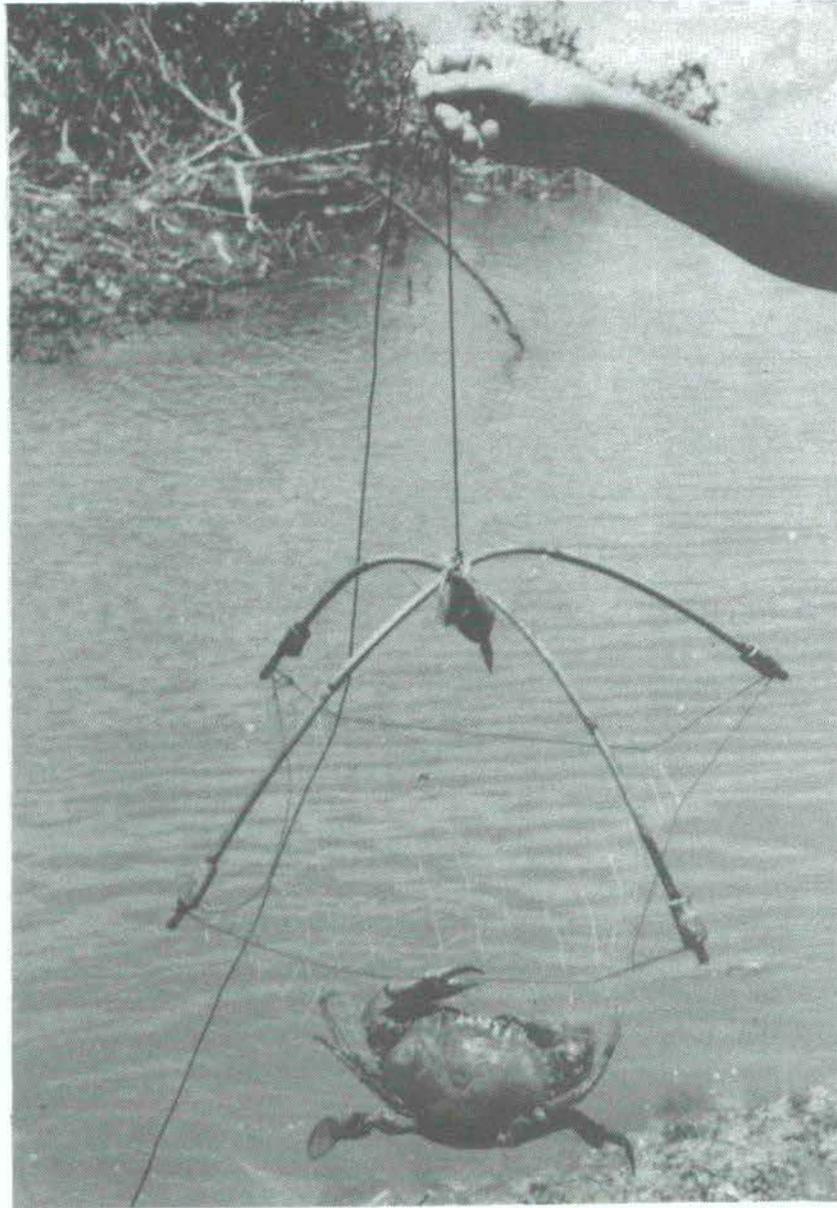

Figure 3: The mangrove crab, *Scylla serrata*, caught in a simple trap (Photo D.J. Macintosh).

Table 3

Number of animal species recorded in mangrove systems in four geographical regions: A=Asia, B=Oceania, C=east coast of Americas; and D=east coast of Africa and the Middle East (modified from IUCN, 1983).

Animal Taxa	A	B	C	D
Protozoa	18		3	
Bryozoa	5	7	36	1
Coelenterata-Ctenophora	3	6	42	12
Non-polychaete worms	13	74	13	3
Polychaeta	11	35	33	72
Crustacea	229	128	87	163
Insecta-Arachnida	500	72		
Mollusca	211	145	124	117
Echinodermata	1	10	29	23
Ascidia	0	8	30	13
Pisces	283	156	212	114
Reptilia	22	3	3	
Amphibia	2		2	
Aves	177	244	138	
Mammalia	36	7	5	

4. EXPECTED CLIMATE CHANGE

Many reports have been published which address the question of global climate change (GCC) that might arise as a result of the activities of man and which examine the possible effects. In particular the following three publications have addressed these issues in great detail: IPCC (Intergovernmental Panel on Climate Change) Climate Change: The IPPC Scientific Assessment. (1990a); IPCC Climate Change: The IPCC Impacts Assessment (1990b); IPCC Climate Change: The IPCC Response Strategies (1991). This review will not attempt to reiterate the extensive discussion that exists on the relatively short term changes to the global climate that are likely to result from the activities of man. It will try to summarise the key predictions and then examine what these may imply for the future of mangrove ecosystems.

Global climate has large natural variability at all time and space scales. It is known from geological records that the recurrent variation in the eccentricity of the earth's elliptical orbit around the sun causes 0.2% variation in the amount of solar radiation intercepted by the earth with a period of some 100,000 years. The minimum of this cycle is known to result in the lowering of the global mean temperature and to produce the phenomenon of a glacial period. These variations of climate on a geological time scale are not our main concern but a knowledge of the effects may give guidance as to what to expect if significant climate changes occur on a much shorter time scale.

It is known that global warming can be caused by green-house gases. These are gases which can absorb infra-red radiation. The absorption of longwave thermal radiation in the atmosphere, thus preventing the escape of thermal energy, causes the temperature of the atmosphere to rise markedly. The natural presence of these gases causes the earth to be warmer than it would be otherwise. The main green-house gases are carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons (CFCs). The commencement of the industrial revolution lead to great amounts of fossil fuel being combusted and the subsequent discharge of large amounts of carbon dioxide to the atmosphere. Since then the activities of man have been continuously elevating the concentration of green-house gases in the atmosphere. Table 4 summarizes the expected changes to the concentration of atmospheric gases, global mean temperature and global mean sea level as predicted by the IPCC.

The atmospheric carbon dioxide concentration in 1990 was 353ppmv, which is about 25% greater than the pre-industrial (1750-1800) value of about 280ppmv, and higher than at any time in the last 160,000 years. Carbon dioxide concentration is currently rising at about 1.8 ppmv (0.5%) per year due to anthropogenic emissions. It has been estimated that atmospheric carbon dioxide concentration will increase to 840 ppmv by the year 2100.

It has been estimated that average global warming has been between 0.3°C and 0.6°C since the late nineteenth century. The temperature record shows significant differences between the Northern and Southern Hemispheres. It has further been estimated that the rate of increase of global mean temperature during the next century will be 0.3°C per decade with an uncertainty of 0.2°C to 0.5°C per decade. This will result in a likely increase in global mean temperature of about 1°C above the present value by 2025 and 3°C before the end of the next century. This estimate is based on the assumption that present rates of emission continue but makes allowances for population expansion and continued economic growth. It may be considered to be a worst case scenario. It is interesting to note estimates that in the tropics the warming will be both smaller and vary little with season. The reason is that the saturation vapour pressure of water varies non-linearly with temperature, so that at higher temperatures proportionally more of the increase in radiative heating of the surface is used to increase evaporation rather than to increase surface temperature.

The effect of climate change in coastal areas is still very speculative (Holligan, 1990; Alusa & Ogallo, 1992). However, the main coastal impacts are likely to be due to (a) sea-level rise as a result of eustatic sea-level rise and local or regional processes responsible for sea-level change between sites; (b) changing hydrological regimes (rainfall, evapotranspiration, runoff, salinity); (c) changes in coastal ocean-atmosphere climate (waves, winds, currents); and (d) increase in tropical storm frequency, magnitude, and occurrence. Each of these effects will display great local variability, and therefore local measurement programmes will be required to document and understand current global change (IOC, 1991; Kjerfve *et al.*, 1991). Only then will it be possible to predict with confidence coastal impacts associated with future climate change.

Table 4

Global man-induced conditions expected at the end of the next century as a result of the IPCC "business-as usual" scenario (IPCC, 1990a).

Atmospheric Greenhouse Gasses	1990		Current Rate of Change	2100	
Carbon Dioxide	353	ppmv	+0.5 %yr^{-1}	840	ppmv
Methane	1.72	ppmv	+0.9 %yr^{-1}	4	ppmv
CFC-11	280	pptv	+4.0 %yr^{-1}	630	pptv
CFC-12	480	pptv	+4.0 %yr^{-1}	1400	pptv
Nitrous Oxide	310	ppbv	+0.25 %yr^{-1}	420	ppbv
Global Mean Temperature (land surfaces warm more rapidly than oceans)			+0.3°C/decade (uncertainty: 0.2-0.5°C/decade)	+3.0°C	
Global Mean Sea Level (mainly due to thermal expansion and melting of some land ice)			+6.0 cm/decade (uncertainty: 3-10 cm/decade)	+60.0 cm	

There is no consistent global trend with respect to tropical and subtropical hydrology and ocean climate changes, but local sea level is likely to rise in many coastal locations, although not necessarily everywhere. Although rising sea level will result in the melting of small and large glaciers, only minor effects on the ice caps are expected to occur (Peltier & Tushingham, 1989; Stewart *et al.*, 1990). During the past century, eustatic sea level rose 0.15 m (National Research Council, 1990; Stewart *et al.*, 1990). Predictions of global sea-level rise as high as 4.5 m during the next century have been suggested (Barth & Titus, 1984), but the best estimate of global sea-level rise is from 0.6 to 1.0m during the next 100 years (Stewart *et al.*, 1990; Houghton *et al.*, 1990).

The absolute vertical rise in global water level is related to climatic warming, but it is the change in sea level relative to land level locally that is measured by tide and water level gauges, and therefore must be analyzed and interpreted, (Pugh, 1987; Stewart *et al.*, 1990; National Research Council, 1990). Relative sea-level change is the combined effect of eustatic sea-level rise and local-regional effects due to (a) large scale tectonic processes (shift in centre of gravity of earth, slight deepening of ocean basins, warping of continental margins, isostatic rebound, and other effects); (b) anthropogenic activities (e.g. extraction of ground water and hydrocarbon deposits, or changes in sedimentation patterns as a result of dam construction and other coastal developments); and (c) changes in the patterns of ocean-atmosphere dynamics along different coasts (Stewart *et al.*, 1990; Kjerfve, 1991).

If global average temperatures rise the evaporation of water from land and water surfaces will rise. Most recent reviews of experiments with general circulation models (Gleick, 1992) suggest that global average precipitation may increase by 3-15% for a build-up of greenhouse gases equivalent to a doubling of the pre-industrial concentration of atmospheric carbon dioxide. The greater the warming the larger the expected precipitation increases. All models predict a greater precipitation in the tropics throughout the year. A warmer climate is also likely to result in more favourable conditions for the formation of tropical storms. Tropical storms form where the sea surface temperature exceeds 26°C (Anthes, 1982), which is likely to be the case over larger ocean areas and for longer periods each year as compared to the present situation. As a result, tropical storms might be expected (a) more frequently, (b) in coastal areas where tropical storms currently do not exist or are rare, and (c) which on average have a greater magnitude than at present (Sylva, 1986; UNEP/UNESCO, 1992a). However, global (climate) circulation models (GCMs) fail to yield consistent indications of the frequency and intensity of tropical storms as the climate warms (Houghton *et al.*, 1990). Nevertheless, the synergistic effect between sea-level rise and storms is likely to be the predominant way in which rising sea level locally will have the greatest impact on coastal areas. Areas not previously affected may suddenly become inundated by sea water during storms, causing salt water to become trapped in depressions, irreversibly prompting soil and vegetation changes (Stewart *et al.*, 1990; Kjerfve *et al.*, 1991). Principally, it is in this manner that relative sea-level rise will impact coastal areas episodically, sometimes with catastrophic results, as the marine systems invade adjacent terrestrial ecosystems.

As global climate change occurs, most coastal sites, including mangrove coasts, are likely to experience relative sea-level rise, changing regimes with respect to precipitation, hydrology and ocean-atmosphere effects, and frequent and more destructive impacts by storms. Since these processes and impacts will vary greatly between coasts, any monitoring programme to be implemented must necessarily be conducted at many and diverse sites, representing different geographical areas.

5. EFFECT OF RELATIVE SEA-LEVEL RISE

In the face of rising sea level, mangroves will retreat landward. If the width and the gradient of the intertidal area remains more or less constant, there is unlikely to be a contraction in the area of mangroves, unless the rise in sea level occurs at a rate that exceeds the capacity of mangroves to migrate landward. However, where the landward margins are already at the boundary of steeply elevated land or barriers constructed by man, there certainly will be constraints on inland migration of mangroves (Kjerfve *et al.*, 1991).

5.1 EROSION WITH SEA-LEVEL RISE

About seventy percent of the world's sandy coasts have eroded in the past few decades. The opinion is spreading among the specialists involved in studying coastal processes that there may be an

increase of the global erosion pattern (Hanson & Linth, 1993). Accelerated coastal erosion is known to be associated with rising sea level (Stewart, et al., 1990). Increased efficiency of wave erosion with a higher sea level causes removal of sediment from the upper part of the tidal spectrum and deposition in the lower part (Bruun, 1962; Committee on Engineering Implications of Changes in Relative Mean Sea Level, 1987). This phenomenon is expected to cause significant beach erosion problems if predicted sea-level rise occurs (Leatherman, 1989: Gornitz, 1991). Coastal sedimentary systems of finer grain size than beach sediment, such as salt marshes and mangrove swamps, could be expected to show a more sensitive response.

It has been shown from Bermuda that mangrove sediments are subject to erosion with rising sea level, with removal of mangrove substrate (above MSL) and with some deposition subtidally offshore of the mangroves (Ellison, 1992 & 1993). Sheet erosion occurs at the peat surface, indicated by a 20 to 25 cm difference between the peat level above a small cliff, and the former peat surface as indicated by exposed horizontal roots of Avicennia. Then as trees recede and loosen the sediment, more rapid erosion occurs to form a 40-45 cm small cliff.

Erosion patterns in mangroves in N W Australia have been described by Semeniuk (1980) showing reverse succession as elevation declines. The effect of sheet erosion on mangrove zonation was migration of seaward mangroves into more landward zones. The effect of cliffing on mangrove zonation was loss of the seaward zone, leading to truncated zonation and narrow fringes.

Mangrove soils are mostly anaerobic and metabolism is driven by sulfate reduction. Erosion along the seaward margins of mangrove systems will expose mangrove soils, which previously were located further away from the margins, and thus were more reduced (lower E_h) and less productive compared to more oxidized creekbanks or shore face environments. This in turn may lead to greater vegetation productivity. Greater productivity eventually leads to greater rates of decomposition, and thus sulfate reduction, and/or greater rates of carbon burial. Overall, the most likely outcome is to transform that part of the mangrove soil system that was characterized by low productivity, reduced soils, and sluggish sulfur cycle, to one which is more productive, better oxidized, and in which the sulfur cycle is more rapid.

The impact on soil acidity (pH) by erosion-induced oxidation of formerly reduced sediments depends on the interplay between the rate of pyrite oxidation, the rate of removal of acidity by drainage, and the buffering capacity of pore water and sediments (Gardner et al., 1988; Gardner, 1990). The rate of pyrite oxidation is for the most part limited by the transport of oxygen into the sediment. In sea water, alkalinity exceeds dissolved oxygen by about a factor of ten. Thus, if oxygen transport is due solely to advection of sea water into the sediments (by burial and infiltration to replace water loss by transpiration and seepage), pyrite oxidation will not significantly lower the pH. Thus, substantial lowering of pH by pyrite oxidation requires substantial advection of air into the sediments by bioturbation, desiccation, and/or root transport. These processes are difficult to quantify. Also, organic matter oxidation competes with pyrite as a sink for oxygen that enters the sediments. Thus, in the absence of abnormal advection of air into mangrove sediments, substantial lowering of pH is unlikely. In the absence of substantial pH lowering, mobilization of trace metals is unlikely, especially if sulfate reduction is still able to produce measurable concentrations of dissolved sulfide.

The situation that may pertain after a significant rise in sea level is difficult to predict. There is evidence from the Mahakam delta, Kalimantan, Indonesia (Caratini & Tissot, 1988) that during the Early Holocene, the pace of the rise in the sea level had been higher than the rate of sedimentation. The sea-level rise could be easily followed through the palynological contents of the sediments since the rise resulted in a shifting of the shoreline towards land and in the subsequent landward progression of the mangrove vegetation. The succession of palynological assemblages was entirely compatible with the present day vegetation zonation of the delta.

In the Manhakam delta, during the highstand sea level of the Late Holocene, a seaward shift of the vegetation zone occurred due to the high sediment supply and the resulting aggradation. Subsidence was also active during this period. The geomorphological evolution results from a combination of these factors, as well as others such as marine currents which, in this region, play an active role in the transportation of the sediments reaching the sea. It appears that in the case of the Mahakam delta during the Holocene transgression, the sedimentation intensified leading to an aggradation and not erosion. Other examples of Late Holocene evolution of mangrove vegetation are given in Thanikaimoni (1987).

5.2   BIOGEOCHEMICAL IMPLICATIONS

Several biogeochemical process occurring in mangroves will be affected by sea-level changes. Changes in the processes involving either the Carbon cycle or nutrients, would probably have the most impact on the mangrove ecosystems and adjacent ecosystems which are linked to mangroves through these cycles (Kjerfve and Lacerda, 1992; Snedaker and Sylva, 1987; Vicente, 1989).

Mangroves extend over some 75% of tropical and sub-tropical shores. Mean annual Carbon production in mangroves is highly variable depending on diverse environmental variables, however over 80% of global carbon production from the mangroves occurs close to the Equator, between latitudes 10°N and 10°S (Twilley et al., 1992). Annual production typically ranges from 1.0 to 8.0 tC.ha^{-1}. In general export of mangrove carbon to coastal areas ranges from 10% to 40% depending on forest structure and tidal regime. A part of the production is locally consumed by mangrove dwelling animals (from 1% to 25%) while most of the production is generally accumulated in mangrove sediments (up to 60% of the total production).

The total amount of Carbon globally accumulated in mangroves is relatively small, when compared to other tropical ecosystems such as the tropical rain forest (Twilley et al., 1992). However, Carbon burial rates may reach up to 35Mt. yr^{-1} globally (Lacerda et al, 1991), this amount is important when compared to the total amount of terrestrial Carbon believed to be buried yearly in coastal and deltaic sediments (circa 180 Mt, Berner (1982)). Although the mangrove area is small relative to the total global forested area, it is located in a key part of the oceans, the tropical shallow seas, where the most complex steps of the Carbon, nutrients and trace substances cycles occur and where most of the organic Carbon in the sea is deposited and accumulated (Deuser, 1988).

Mangrove sediments are typically composed of fine clays rich in organic matter. Semi-permanent flooding reduces oxygen diffusion through the sediment resulting in an anoxic sedimentary environment. Therefore the metabolism of mangrove sediments is anaerobic, based on the reduction of sulphate by bacteria. Under such conditions, organic matter is only partially degraded and an accumulation of organic compounds occurs. Relatively high sedimentation rates help in the burial of this partially decomposed organic matter which is then preserved (Lacerda and Rezende, 1990; Lynch et al., 1989).

Studies on the erosive capacity of tides have been conducted over 3 years at the Itacurussá Experimental Forest, a small, 4.0 ha Rhizophora fringe forests located in SE Brazil (Lat. 23°S) (Rezende et al., 1990; Lacerda et al., 1991). Mass balances based on different tidal cycles showed that spring tides when associated with cold fronts, are able to erode sediments deposited on the forest.

There is a significant, exponential relationship between tidal amplitude, flooded area and the quantity of organic matter eroded and transported from the forest. Since the relationship is exponential, minor increases in tidal amplitude which is a most probable effect of relative sea-level rise (RSLR), will have little effect at lower tidal amplitudes but will significantly increase erosion during high tidal amplitudes, in particular during storm events. Therefore a net erosive pattern is expected.

Mangroves are open systems that use marine and terrestrially derived CO_2 to support high rates of primary production. A significant proportion (~ 40%) of it is ultimately transferred back to the environment via litter fall. Balance studies carried on in many mangrove sites worldwide, have shown that most litter fall is trapped and eventually buried in mangrove sediments. Stable isotopes studies have confirmed that nearly 100% of sediment carbon in mangroves originates in the mangrove biomass itself. This Carbon can be accumulated and reaches very high concentrations (up to 20% d.w.) (Risk and Rhodes, 1985), therefore, when erosion of sediments occurs, large amounts of carbon can be also exported to the adjacent coastal areas. Since a proportion of this carbon still has great oxidizable capability, large consumption of oxygen is expected when this eroded material reached the oxygen rich coastal waters (Emeis, 1987). Evidence of such effects has been found in the sedimentary record of coastal seas worldwide (Haake, 1987; Emeis, 1990; Neev and Emery, 1990; Willwock, 1987). Theoretical modelling of past RSLR events predicted eutrophication of coastal waters (Emeis, 1987).

Other chemical constituents which present a similar cycle to that of organic carbon, may suffer similar processes. Nitrogen is rapidly recycled to ammonia and elemental Nitrogen (N_2) under conditions prevailing in mangroves (Ovalle et al., 1990; Nordwell, 1975). However, oxidation of mangrove sediments

due to RSLR, will probably result in increasing nitrification, leading to nitrate enrichment of outwelling waters and therefore causing eutrophication of coastal waters.

Finally, another group of elements of environmental importance, the trace metals, may also change their biogeochemical fate depending on RSLR. Most trace metals, in particular the more toxic Hg, Pb, Cd, Zn and Cu, accumulate to high concentrations in mangrove sediments, where they are immobilized as insoluble sulfides which are non-available to biological uptake (Lacerda and Abrao 1984; Harbinson, 1984; 1986). However, upon oxidation of waters and sediments, most of the recently formed metal sulfides dissociate, liberating trace metals to solution where they attain their maximum bio-availability (Lacerda et al., 1988). Therefore under the expected conditions created by RSLR, where pulses of oxidation-erosion forces are expected, acute release of accumulated trace metals may occur threatening mangrove and other coastal food chains.

The expected impact upon biogeochemical reactions of mangrove ecosystems due to RSLR is difficult to predict. There is a need to monitor such process along erosive coasts so that the full impact can be estimated.

5.3   RELATIVE SEA-LEVEL CHANGE AND GEOMORPHIC SETTING

Mangroves occurring in carbonate settings are likely to be the most vulnerable to a rise in relative sea level. Carbonate settings are usually associated with oceanic islands and coral atolls where physiographic conditions may limit the landward progression of mangroves as relative sea-level rises. Furthermore, sedimentation in carbonate settings is predominantly autochthonous and less likely to keep pace with sea-level rise than that in river-dominated systems which receive large volumes of allochthonous sediments from upland catchments (Woodroffe, 1990).

Stratigraphic records from a number of islands in the Caribbean and Pacific (some of which have carbonate settings) (see Table 1) suggest that the mangroves there had difficulty in keeping pace with the changes in sea level that occurred during the Quaternary period (Ellison & Stoddart, 1991). On the basis of these records and data from other sites, Ellison & Stoddart (1991) concluded that "... in the absence of significant allochthonous sediment input, mangrove ecosystems appear to be able to keep pace with a rising sea level of 8-9 cm per 100 calendar years, are under stress at rates between 9 and 12 cm per 100 calendar years, and cannot persist in their expansive mode at rates above this." However, it should be noted that carbonate settings are not fully representative of the majority of mangrove ecosystems.

Tide-dominated systems are usually characterized by a large tidal range (Woodroffe, 1990). In macrotidal estuaries, tidal influences often over-ride the riverine influences, and vertical accretion within the mangrove ecosystem is due chiefly to tidally-driven reworking and transport of marine sediments. Woodroffe (1990) gives several examples of such tide-dominated systems in northern Australia. The rate of accretion will be approximately commensurate with local sea-level rise, as long as adjacent waters have sufficient sediment sources. The explanation for this is natural trapping or filtering of sediments. Currents loose the capacity for sediment transport as water velocities are decreased by mangrove prop roots, other vegetation, and shallow water depths (Wolanski et al., 1980). The evolution of these estuarine plains in northern Australia appears to have taken place in three phases. During the period 8000-6000 years BP, when sea level rose by 12 m, there was an average annual rate of vertical accretion of about 6 mm, and mangrove vegetation kept pace with the rise in sea level (Woodroffe, 1990). This was followed by a big swamp phase (6800-5300 years BP) during a period of relative stability in sea level (Woodroffe et al., 1985). Since that time, mangrove forests have become reduced in area as sediments built up to a level at which tidal flooding ceased (Woodroffe, 1990).

With the presently predicted rate of rise in sea level of 5 to 10 mm per year over the next 100 years, it is possible that this cycle will be repeated in northern Australia and in other tidally-dominated systems that followed a similar pattern from 8000 years BP to present. In such settings re-establishment and expansion of mangroves on formerly tidal floodplains might be expected.

River-dominated deltaic environments are characterized by the influx of large volumes of allochthonous sediments washed down-river from eroding catchments. The deposition of fluvial material to form large intertidal deltas that are opportunistically colonized by mangroves has led in the past to seaward extension of mangrove areas, as for example in the Gulf of Papua. Provided that there is no

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significant change in rainfall patterns in the catchments of river-dominated settings, it seems likely that vertical accretion of sediment will keep pace with the predicted rate of rise in sea level, or at least will reduce the rate at which mangroves contract in such settings.

The stratigraphic record of the impact of past sea-level changes on the extent and zonation of mangrove ecosystems suggests that sedimentation rates in some geomorphic settings have kept pace with changes in sea level for an appreciable time. Under such conditions, there has been minimal disruption to mangrove ecosystems, while in other settings the rate of past rises in sea level have outstripped sediment accretion, leading to major disruption of mangrove ecosystems. There is, however, much uncertainty about the extent to which the impact of a future rise in sea level on mangrove ecosystems can be predicted from past stratigraphic records. Inferences based on past records assume that geomorphic settings, tidal regimes, rainfall patterns, catchment hydrology and fluvial inputs have remained largely unchanged over the past 6000 years (Coleman *et al.*, 1970), and will not be modified perceptibly in the future by human activities.

It is likely that mangrove ecosystems on small islands would be severely disrupted by a local rise in eustatic sea level, but it is difficult to predict the impact on mangrove ecosystems along continental shorelines. However, the synergistic effect between local rising sea level and episodic storm impacts is likely to be particularly destructive to low island mangrove systems (Stoddart, 1965, 1969, 1974).

6. RESPONSE OF MANGROVE FLORA TO CLIMATE CHANGE

6.1. TEMPERATURE CHANGE AND FLORA DISTRIBUTION

The present latitudinal extremes for the distribution of mangroves correspond well with an average minimum sea-surface temperature of 24°C, although minimum sea temperatures may be somewhat lower than these average values for part of the year (Tomlinson, 1986). Average minimum air temperatures at these extremes are much lower. Only a few studies have been published on the lower temperature threshold for individual mangrove species. McMillan (1971) and Markley *et al.* (1982) reported marked genotypic variability and/or phenotypic plasticity in survival and growth of several mangrove species at low temperatures.

In principle, it is reasonable to expect that a rise in mean regional sea-surface or air temperatures (or both) might lead to the progression of some species of mangroves to higher latitudes, provided that the direction of prevailing ocean currents favours dispersal of the propagules. Extension of the latitudinal range of mangrove species is likely only in regions where temperatures rise by more than several degrees, and even then will take some time (perhaps three or four decades) to become evident.

6.2. TEMPERATURE CHANGE AND MANGROVE PHENOLOGY

The reproductive and vegetative phenology of mangroves shows marked geographic and intraspecific variation. In environments with a distinctly seasonal climate, flowering and growth often appear to be correlated with the onset of warmer summer temperatures and/or monsoons, but such correlation is sometimes confused by irregularities for which there is yet no consistent explanation (Gill & Tomlinson, 1969; Christensen & Wium-Anderson, 1977; Tomlinson *et al.*, 1979; Williams *et al.*, 1981; Duke *et al.*, 1981, 1984; Saenger, 1982; Saenger & Moverley, 1985; Tomlinson, 1986). In the humid tropics, however, flowering of Rhizophora spp. generally occurs all the year round (Chai, 1982; Macintosh *et al.*, 1991). Many of these studies have been confined to the genus Rhizophora and relatively little information is available for other genera. Furthermore, the environmental and endogenous triggers that initiate flowering and flushes of vegetative growth in mangroves are not well understood.

In all but the most extreme environments, most mangrove species flower annually. Wind, insects, birds and bats are the main pollinating agents (Saenger, 1982). Several studies have reported a high mortality of flower buds in the family Rhizophoraceae, in some cases with less than 10% of the buds producing mature propagules (Gill & Tomlinson, 1971; Christensen & Wium-Anderson, 1977; Macintosh *et al.*, 1991). Much of this pre-dispersal mortality has been attributed to fungal and insect attack and to morphogenetic defects (Saenger, 1982). Notwithstanding these high levels of pre-dispersal mortality, mature mangrove propagules are usually relatively abundant in many areas (Duke *et al.*, 1981).
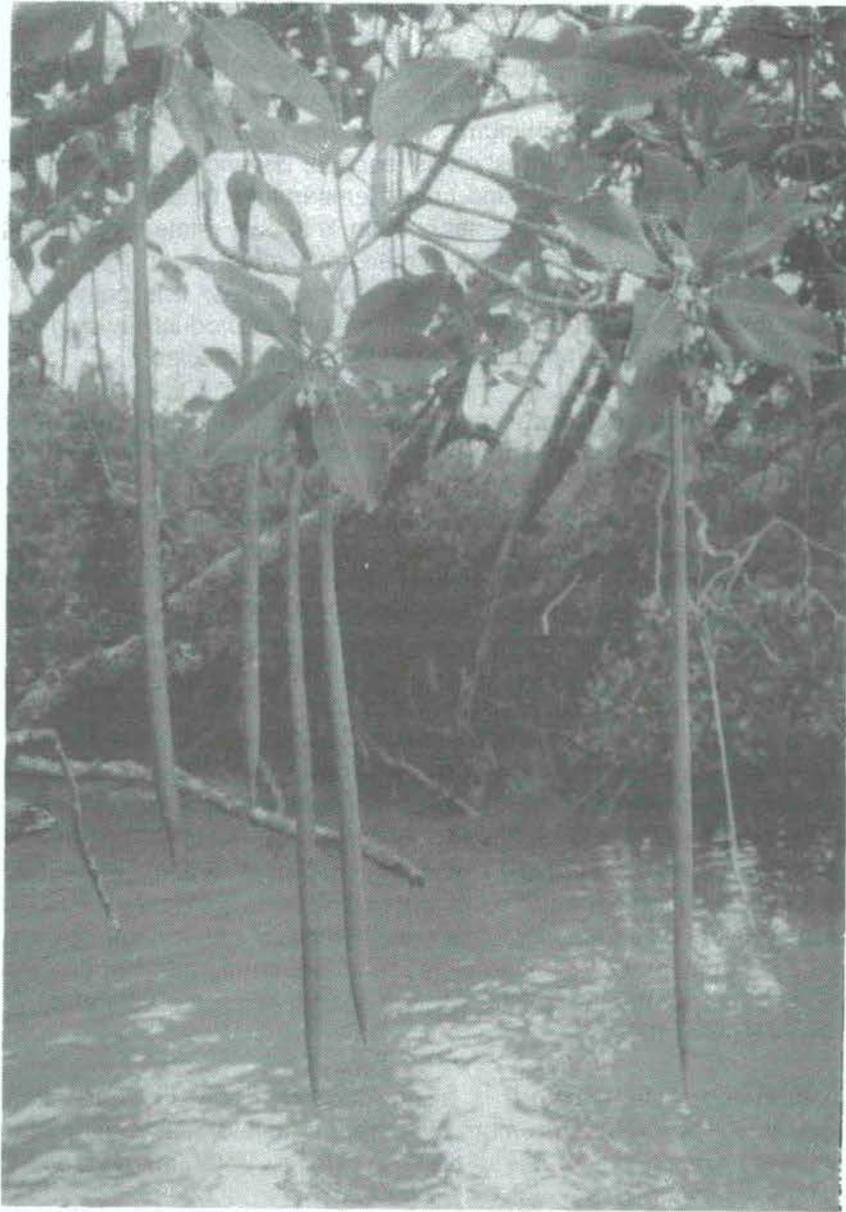
Figure 4: *Rhizophora* **viviparous propagules, East Kalimantan, Indonesia
(Photo D.J. Macintosh).**

Since little is known about the environmental and endogenous factors influencing the phenology of mangroves, it is difficult to predict the effect of an increase in air temperature on their reproductive capacity. In general, an increase in air temperature of less than 1°C seems unlikely to have an adverse effect on the production of flower buds or flower set, but it may change existing seasonal patterns in the reproductive sequence and alter the length of time between flowering and the fall of mature propagules.

Climatic changes that affect mangrove pollinating agents will clearly have some impact on the proportion of flower buds that are pollinated. Furthermore, where the climatic changes increase the risk of attack on the developing propagules, higher levels of pre-dispersal mortality are likely. The additive or synergistic effects of such changes could limit the reproduction of mangroves. An example of *Rhizophora* propagules is shown in Figure 4.

6.3.   TEMPERATURE CHANGE, PRODUCTIVITY AND GROWTH

Temperature affects the rate of metabolic processes in mangroves. The rates of many physiological processes at first increase with temperature up to an optimum temperature level, and thereafter decrease with further thermal increase above this optimum. For other processes, respiration for example, the rate increases with temperature until an upper threshold is reached, beyond which permanent damage or death occurs. Temperature optima, and the lower and upper temperature thresholds, are known for only a few processes in a small number of mangrove species. What is known relates almost entirely to the leaves; almost nothing is known of temperature responses in mangrove roots. Apart from the effect of temperature on photosynthesis, water loss and the water balance of mangroves, it is possible only to make broad generalizations about the effect of changes in temperature on the productivity and growth of mangroves, based largely on information available from studies on other plant species.

Since saturated soils and large water masses, such as the oceans, have a large heat capacity, diurnal and seasonal variations in soil temperature are substantially smaller than those of air temperature, except in cases where the plant canopy is poorly developed and the soil surface is exposed directly to the sun. It is therefore unlikely that soil temperature in mangrove areas will reach the upper threshold beyond which death occurs, even with a rate of global warming much greater than that predicted. However, rising temperature is likely to lead to increased rates of root respiration and increased rates of root growth and turnover (Burchett et al., 1984). In some cases, root respiration and root turnover together account for up to approximately 60% of the total carbon fixed in photosynthesis (Clough, 1992). Consequently, even a small increase in the rates of these processes as a result of rising temperature will lead to a significant reduction in growth.

In the mangrove canopy it is plant temperature (of the leaf or stem), rather than air temperature, that is the critical factor in terms of canopy processes and growth. During the daytime, interception of solar radiation by leaves causes their temperature to rise significantly (10°C or more) above ambient air temperature (Clough et al., 1982). A rise in global temperature will therefore increase the baseline temperature above which leaf temperature rises on exposure to sunlight. Elevated leaf temperatures increase the rate of respiration. They also increase photosynthesis at temperatures below the optimum for photosynthesis (28-32°C in mangroves), but an increase in leaf temperature above about 32-35°C results in a dramatic reduction in photosynthesis which falls to near zero at a leaf temperature of 38-40°C (Andrews et al., 1984; Andrews & Muller, 1985).

At night, mangrove leaf temperature is highly dependent on air temperature. Night-time leaf temperatures are usually well below the maximum temperature limit for leaf metabolism. Increases in night-time temperature, will lead to increased rates of dark respiration, both in leaves and woody tissues.

Unfortunately, few data exist for rates of respiration of the woody above-ground parts of mangrove trees. For leaves, respiratory losses overnight are an order of magnitude lower than those of the roots. Thus the effect of changes in air temperature on canopy respiration can be expected to be small compared to the effect of changes in soil temperature on root respiration and turnover.

6.4.   TEMPERATURE CHANGE, MICROBIAL ACTIVITY AND NUTRIENT
CYCLING

Mangrove ecosystems contain large microbial populations that are intimately involved in detrital decomposition and nutrient recycling (Alongi, 1989). Numerically, bacteria represent the largest fraction of the microbial population in mangrove sediments. Meiofauna communities are also abundant in mangrove soils.

With an adequate supply of organic carbon as a substrate, bacterial metabolic and growth rates should increase with temperature. The limited field data available, however, indicate considerable inter-estuary variation in seasonal patterns of bacterial numbers and of their metabolic and growth rates. Alongi (1987a, 1988a,b) reported significantly higher bacterial counts in winter than in summer for estuaries in monsoonal climates in north-eastern Australia, whereas there was no pronounced seasonality in bacterial densities of mangrove sediments in the dry tropics (Alongi, 1987a, 1988a,b). This was attributed to scouring of the surface layers of the sediment by summer monsoonal rains. Notwithstanding the lower bacterial

densities in the wet tropics during the summer, bacterial productivity was generally higher, and bacterial growth rates were up to four times faster in the summer than in winter (Alongi, 1988a).

These observations suggest that an increase in sediment temperature will lead to increased rates of nutrient recycling and regeneration in mangrove ecosystems. The magnitude and rate of increase in sediment temperature is likely to be of the same order as that of sea surface temperature. The long-term effect on microbial activity and nutrient cycling is difficult to predict.

6.5.   SOLAR RADIATION CHANGE AND MANGROVE FLORA

On an average clear sunny day the earth's surface receives a maximum of about 1000 W m^{-2} of short-wave solar radiation consisting of about 50% visible light (400-700 nm) and 50% infrared (IR) radiation (Monteith, 1973). The flux density of ultraviolet radiation (UV < 400 nm) is a very small but biologically active component of the shortwave spectrum. Cloud, dust, other particulates, and various gases all absorb different wavelengths in the shortwave spectrum and therefore reduce the radiation flux density at the earth's surface. All three of these radiation bands are absorbed by plant foliage.

6.5.1.   UV Radiation

The flux of UV radiation on the earth is greatly reduced by absorption in the ozone layer of the stratosphere and by scattering in the atmosphere. The chemical reaction of ozone with a number of gases released in greater quantities by industrial and other human activities has led to the depletion of ozone in the stratosphere, notably in the antarctic and temperate regions of the southern hemisphere, with a consequent increase in the flux density of UV radiation reaching the surface of the earth (Peixoto & Oort, 1992).

High levels of UV-B radiation (280-320 nm) have been found to depress photosynthesis and to reduce plant growth (Caldwell, 1981; Tevini & Teramura, 1989), the former response being attributed to stomatal closure (Teramura et al., 1983; Negash, 1987) and to effects on protein synthesis and denaturation (Strid et al., 1990). A variety of critical, biologically active molecules, including nucleic acids, proteins pigments and lipids, preferentially absorb UV-B radiation (Caldwell, 1981) that converts them to unstable states.

In many plant species, protection against the potentially damaging effects of UV-B radiation is provided by natural UV absorbing compounds, mainly tannins or phenolic compounds such as flavones, flavonols, and esterified anthocyanins (Tevini et al., 1991). Mangrove leaves contain high levels of tannin (Robertson, 1988; Lovelock, 1991). Recent work has shown that exposure to UV radiation stimulates the synthesis of UV absorbing compounds in the leaves of mangroves (Lovelock, 1991). This is often associated in mangroves with an increase in leaf succulence and the extent to which this occurs seems to be species dependent (Lovelock, 1991).

However, it is still not clear whether the capacity to synthesize phenolic compounds is sufficient to avoid damage from elevated levels of UV-B radiation. Even if it is, growth is nevertheless likely to be reduced at higher levels of UV-B radiation because of the greater diversion of energy resources to the synthesis of UV absorbing compounds.

6.5.2.   Visible Radiation

Interception and absorption of visible solar radiation (400-700 nm) by plant leaves is essential for photosynthetic carbon fixation. The maximum photon flux density (PFD; 400-700 nm) at the earth's surface on a clear sunny day is about 2500 mmol photons m^{-2} ground s^{-1}, but depending on latitude and time of the year seldom exceeds about 2200 mmol m^{-2} s^{-1}. The rate of photosynthesis in mangrove leaves is a linear function of PFD up to a PFD of about 200 mmol m^{-2} s^{-1} and thereafter shows a more or less hyperbolic response to increasing PFD, commonly reaching a light-saturated maximum at about 600-800 mmol m^{-2} s^{-1} or about 1/3 full sunlight, beyond which there is no increase in photosynthetic rate with further increase in PFD (Moore et al., 1972; Moore et al., 1973; Attiwill & Clough, 1980; Ball & Critchley, 1982; Andrews et al., 1984; Cheeseman et al., 1991; Gong et al., 1992). Mangrove leaves exposed to bright sunshine therefore receive visible radiation in excess of that which can be utilized effectively for photosynthesis (Andrews et al., 1984; Andrews & Muller, 1985; Björkman et al., 1988; Lovelock & Clough, 1992). In some species,

dissipation of this excess radiation leads to decoupling of the electron transport chain of Photosystem II, giving rise to a phenomenon known as photo-inhibition (Björkman *et al.*, 1988). In other species, this excess visible radiation appears to be dissipated relatively harmlessly through the xanthophyll cycle (Lovelock & Clough, 1992).

6.5.3. Infrared Radiation

Absorption of infrared (IR) radiation by mangrove leaves in excess of that which can be dissipated by radiative, convective and evaporative cooling causes leaf temperature to rise. In bright sunshine, leaves that are normal to the sun's rays may be up to 10°C warmer than the air around them and in extreme cases may reach temperatures of 40°C or more (Andrews *et al.*, 1984; Andrews & Muller, 1985). The optimum leaf temperature for photosynthesis in mangroves appears to be in the region of 28-32°C (Moore *et al.*, 1972; Moore *et al.*, 1973; Clough *et al.*, 1982; Andrews *et al.*, 1984; Andrews & Muller, 1985). At higher leaf temperatures, photosynthetic capacity is greatly reduced, falling to close to zero at leaf temperatures of 38-40°C (Andrews *et al.*, 1984).

In a number of species, mainly members of the family Rhizophoraceae, the more exposed leaves at the top of the canopy are steeply inclined, while those in more shaded positions lower in the canopy are more horizontally disposed. This is clearly an important adaptation to optimize absorption of sunlight by the canopy as a whole, while minimizing the absorption of potentially damaging levels of solar radiation by leaves in more exposed positions at the top of the canopy (Clough *et al.*, 1982; Andrews & Muller, 1985; Ball *et al.*, 1988).

6.6. HYDROLOGICAL CHANGE AND MANGROVE FLORA

It is readily observed that mangroves growing in persistently wet, humid climates grow faster and attain greater stature than those in drier climates or in climates where there is a pronounced seasonality. These differences in growth rate reflect interactions between photosynthetic CO_2 exchange, evapotranspiration, plant water stress, and the availability of water to the trees (Tomlinson, 1986; Clough, 1992).

Soil water content and soil salinity are major factors influencing the water status of mangroves. For those mangrove soils that are tidally inundated regularly and thus waterlogged (perhaps the majority of mangrove soils), soil water content *per se* is seldom a limiting factor. However, for mangroves growing near the landward margins, where tidal inundation is infrequent or irregular, the physical availability of water may be limiting, thereby inducing plant water stress.

Most mangrove soils, on the other hand, have moderate to high soil salinities. All true mangrove species possess physiological and morphological adaptations that confer a degree of salt tolerance which varies from one species to another (Clough *et al.*, 1982; Saenger, 1982; Popp, 1984a,b; Popp *et al.*, 1984; Clough, 1992). In saline, waterlogged soils, the osmotic potential of the soil solution is the main component of soil water potential. In the case of a soil with a salinity of seawater, the soil water potential (= osmotic potential) is of the order of -2.5 MPa; this is the highest plant water potential that can be attained overnight. During the daytime, when water loss from the canopy generally exceeds water uptake, mangrove plant water potentials fall to even more negative values, often as low as -5 MPa (Smith *et al.*, 1989; Gong *et al*, 1992). It is assumed that in mangroves, as in other plant species, growth is much reduced by low plant water potentials. This assumption is consistent with the response of mangrove seedlings to salinity, in which growth is reduced at soil salinities above about 20ppt (Connor, 1969; Downton, 1982; Clough, 1984). It is also consistent with the much depressed rates of growth of natural mangrove forest in areas with high soil salinity.

Evapotranspiration from mangrove canopies is driven by the vapour pressure difference (VPD) between the leaves and the surrounding air which, in turn, is influenced by leaf temperature, ambient temperature and relative humidity. The greater the difference between leaf temperature and ambient temperature, the greater the VPD; and the lower the relative humidity, the greater the VPD. Many species of mangrove respond to high VPD and high rates of water loss by partial or complete closure of their stomata (Moore *et al.*, 1972; Moore *et al.*, 1973; Andrews *et al.*, 1984; Ball & Farquhar, 1984a,b; Andrews & Muller, 1985; Clough & Sim, 1989; Smith *et al.*, 1989), thereby reducing the rate of water loss. However, when mangrove leaves are much hotter than their surroundings (as in the case where they are exposed to

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direct bright sunshine), stomatal responses are usually not sufficient to offset the effect of high VPD (Andrews & Muller, 1985; Ball et al., 1988), and the leaves continue to lose water at a rate faster than it can be supplied by the roots, leading to low tissue water potentials that reduce metabolic activity and growth rates. As noted above, high soil salinities reduce the availability of water and exacerbate this problem (Clough et al, 1982; Ball & Farquhar, 1984a,b).

The effect of soil salinity and vapour pressure deficit on photosynthetic carbon fixation and water loss by mangroves has been investigated by a number of authors, both in the laboratory (Ball & Farquhar, 1984a,b; Tsilemanis, 1990) and in the field (Andrews et al., 1984; Andrews & Muller, 1985; Clough & Sim, 1989; Smith et al., 1989). Clough & Sim (1989), for example, found that rates of photosynthesis in 19 species of mangrove decreased more or less linearly with increasing soil salinity and increasing leaf-to-air VPD. This condition was accompanied by an increase in water use efficiency (Clough & Sim, 1989).

Mangroves have an unusually high water use efficiency for C3 plants (Clough et al., 1982; Andrews et al., 1984; Andrews & Muller, 1985; Ball, 1988; Ball et al., 1988; Clough & Sim, 1989). This high water use efficiency, which attests to the need to maintain an acceptable plant water balance in a harsh environment, is achieved in part by morphological adaptations such as pubescent leaves and sunken or otherwise hidden stomata (Saenger, 1982; Clough et al., 1982), in part by a canopy architecture that minimizes radiation loading on individual leaves (Andrews et al., 1984; Andrews & Muller, 1985; Ball et al., 1988), and in part by close coordination between stomatal conductance and photosynthetic capacity (Clough et al., 1982; Andrews et al., 1984; Andrews & Muller, 1985; Ball et al., 1988; Clough & Sim, 1989; Cheeseman et al., 1991). These are characteristics that would be expected of plants that are adapted to environments where water is in short supply and/or rates of water loss are high. Both the morphological adaptations to reduce water loss and the physiological responses to salinity and leaf-to-air VPD suggest that mangroves have adopted a general strategy of minimal water use for a given carbon gain.

Changes in local or regional climatic conditions that play a key role in influencing water loss and the water balance of mangrove trees can be expected to have a significant impact on their rate of growth. Climatic changes that can be expected to reduce the rate of water loss from mangrove canopies and hence improve plant water balance include: (a) an increase in the persistence of cloudy conditions (i.e cloud cover for longer periods), which will reduce the leaf-to-air VPD and the precipitation/evapotranspiration ratio, with or without a concomitant increase in precipitation; (b) a decrease in the amplitude of the wet and dry seasons, which should result in a more even distribution of both cloud cover and precipitation throughout the year, particularly in areas where there are now pronounced wet and dry seasons; and (c) an increase in precipitation along presently drier coastlines. Conversely, climatic changes that can be expected to increase rates of water loss from mangrove canopies and hence degrade plant water balance include: (a) a decrease in cloudiness; (b) more pronounced seasonality; and (c) a decrease in precipitation.

In general, a more equitable distribution of rainfall throughout the year in seasonally dry catchments that drain into mangrove areas can be expected to reduce soil salinity, with a consequent improvement in plant water balance and growth rates. To some extent, however, this effect might be moderated by intrusion of sea water further into the mangrove area, should such climatic change also be accompanied by a rise in relative sea level.

6.7.   ATMOSPHERIC CO_2 CHANGE AND MANGROVE FLORA

A change in the atmospheric CO_2 level alters the net carbon balance of the plant by changing the substrate resource but development of the plant will be determined principally by the rate modifier temperature and other controlling factors such as enzyme activity and photoperiod. It is therefore difficult to generalise on the effect of changes of atmospheric CO_2 levels on plant development (Rawson 1992). The question of whether photosynthetic carbon fixation will be enhanced by increasing concentrations of atmospheric CO_2 depends largely on the extent to which photosynthesis is limited by present atmospheric CO_2 concentrations. There is some evidence that elevated CO_2 stimulates plant growth at least in agricultural plant species (Kimball 1983; Cure and Acock 1986) where most of the experiments have been carried out with green house grown plants. Eamus & Jarvis (1989), in an extensive review, reported some enhancement of growth in juvenile trees and Drake (1992) reported a significant impact of enhanced atmospheric CO_2 on a wetland community of sedges and grasses. Though there is evidence that CO_2 enrichment will enhance growth in seedling tree species there is no equivalent evidence that there will be long term forest growth in response to rising atmospheric CO_2. A growth response to CO_2 may be manifest

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in below ground processes of forest ecosystems which tend to be nutrient and water limited. At the whole plant level, carbon isotope composition data indicate species variation in regulation of water loss with respect to carbon gain. The limited data suggest that not all species will respond similarly to elevated atmospheric CO_2 levels.

In laboratory experiments under carefully controlled ambient conditions and a range of salinities, Ball & Farquhar (1984a,b) analyzed the steady-state CO_2 response curves of two species of mangrove (Aegiceras corniculatum and Avicennia marina) and found that the rate of photosynthesis was co-limited by both stomatal conductance to CO_2 and the internal efficiency of carboxylation involving the enzyme RuBP carboxylase. In the two species used in their study, the rate of photosynthesis increased linearly with intercellular CO_2 partial pressure. The observed partial limitation of photosynthetic rate by stomatal conductance implies that photosynthesis could be stimulated by elevated ambient CO_2 concentrations, which would tend to offset the drop in concentration across the partially closed stomatal pores.

In other studies, carried out on mature trees of Bruguiera parviflora, B. gymnorrhiza, and Rhizophora apiculata in the field, it was found that the intercellular CO_2 concentration commonly decreased with increasing rates of net photosynthesis (Cheeseman et al., 1991; Clough et al., unpublished). In the study by Cheeseman et al. (1991), light and stomatal conductance accounted for an average reduction in net photosynthesis of less than 35% from the maximum values predicted by the light and conductance responses. These results suggest that, at least in the field, photosynthetic performance is regulated primarily by internal, non-stomatal, processes (Cheeseman et al., 1991), in which case photosynthetic performance is unlikely to be stimulated significantly by a further increase in ambient CO_2 concentration above the present level.

In those cases where canopy photosynthesis may be partially limited by CO_2 supply because of low stomatal conductance, the key question then is whether or not mangroves will respond to a rise in ambient CO_2 concentration by further closure of their stomata. If the stomatal conductance remains unchanged, then photosynthetic rates are likely to increase. On the other hand, if the stomatal conductance was to decrease in order to minimize water loss, then rates of photosynthesis may not increase to any significant extent. Either of these responses by mangroves will lead to an increase in their water use efficiency.

In view of the "physiological dryness" of most mangrove environments and the importance of maintaining a satisfactory plant water balance at moderate to high soil salinities and vapour pressure deficits, mangroves may respond to increased levels of atmospheric CO_2 by further reduction in stomatal conductance in order to minimize water loss, probably without a concomitant increase in photosynthetic rates. Depending on the magnitude of this reduction in stomatal conductance relative to other factors regulating water loss (mainly leaf-to-air VPD), there may be some increase in the rate of growth owing to an improved plant water balance. Only in the most favourable environments, where water, nutrients and temperature are not major constraints, would there be any significant increase in the rate of canopy photosynthesis in response to increased levels of atmospheric CO_2 above present levels. However, there remains considerable uncertainty about how mangroves will respond to very much higher levels (say twice the present concentration) of atmospheric CO_2.

7.   RESPONSE OF MANGROVE FAUNA TO CLIMATE CHANGE

7.1.   TEMPERATURE CHANGE AND MANGROVE FAUNA DISTRIBUTION

7.1.1. Effect on Geographical Distribution

In general, mangrove ecosystems are sensitive to thermal stress and tropical marine animals show limited ranges of temperature tolerance (Moore, 1972; Hong & Chin, 1983; Paphavasit et al, 1990). Some groups of animals commonly found in mangroves already show apparent speciation in relation to temperature, such as fiddler crabs of the genus Uca (Crane, 1975), suggesting that geographical changes in species distribution will follow from climatic changes in average ambient temperature in mangrove ecosystems.

Temperature related changes in latitudinal distribution are also predictable in the case of aquatic species, since many of these are already known to respond to seasonal temperature changes by migrating

within a given latitudinal range. For example, the various species of penaeid shrimps living in tropical to warm temperate coastal waters show distinct latitudinal ranges delimited by their preferred temperature ranges (Main & Fulks, 1990). It is concluded that, on a geographical scale, the species distributions of mangrove-associated faunal taxa, such as *Uca* and *Penaeus*, would adjust rapidly to any temperature increases caused by climatic change.

Most significant to the distribution of mangrove animals would be losses of exploitable habitats, should climatic change lead to the shrinking of the mangroves away from their present latitudinal limits. Conversely, any extension in mangrove range due to global warming, would create opportunities for range extensions by some mangrove animal species. Observations in new mangrove plantations and experimental study sites in natural forests, have shown that mangrove animals, such as crabs, snails, polychaete worms, insects and birds will colonize new mangrove sites within weeks or even more rapidly (Macintosh *et al.*, 1991).

A large variety of birds is dependent on mangrove areas for feeding, nesting or roosting (Table 3). Important among these are the waterfowl, such as herons, ducks and ibises, whose ecology is intimately connected to the hydrology of mangrove wetlands. Changes in mangrove areal coverage or distribution, degree and periodicity of inundation or invertebrate food organisms are likely to influence bird populations. Mangrove wetlands are very important also as resting and feeding sites for migratory waterbirds. In the Caribbean and Central America they are a critical component of the flyways between North and South America (Scott & Carbonell, 1986). If mangrove loss or reduction occurs as a result of climate change there could be serious consequences for the migratory avifauna of these temperate regions.

7.1.2. Effect on Local Distribution

The thermal environment within a mangrove forest is strongly moderated by the shade provided by the vegetation. This protection from temperature fluctuation is further enhanced for many intertidal mangrove animals by their habit of living in burrows, or under fallen leaves, crevices in decaying wood, and other special habitats (Berry, 1975; Macintosh *et al.*, 1991). Mangrove fiddler crabs, for example, can experience temperatures reaching 41°C on the exposed surface of a mangrove mudflat, but can retreat into their burrows where temperatures remain constant at 28-30°C below 10 cm depth (Macintosh, 1978). Similarly, Smith and Miller (1973) reported that body temperatures of Florida mangrove fiddler crabs dropped by almost 10oC when they entered their burrows. Thus, common intertidal mangrove crabs like Uca and the other ocypodid and sesarmid genera could probably adapt to expected increases in ambient temperature by making more frequent or extended burrow visits to avoid thermal stress. The same would apply to mangrove mudskippers which have a similar dependence on burrowing for thermo-regulation (Macnae, 1968). At the species level, increases in shore temperatures could favour mangrove animals adapted to living within shaded forest areas, and those that are nocturnally active, such as many of the mangrove sesarmid crabs (Malley, 1977).

For other species which live in unshaded habitats, such as mud flats, creek banks and sand pits, their distribution on mangrove shores is generally regulated by a combination of high temperatures and the effects of exposure to desiccation at low tides. Climate changes which lead to higher shore temperatures, or greater exposure to air will act to further limit their intertidal ranges, and such effects should be relatively easy to measure. For some regions at least, there is already a wealth of data on the species distribution of animals in mangroves, particularly the intertidal macrofauna, including quantitative estimates (Warner, 1969; Sasekumar, 1974; Paphavisit *et al.*, 1990; Macintosh *et al.*, 1991). This information can serve as a baseline from which alterations in species composition, distribution or abundance resulting from the impact of climatic change on mangroves may be estimated.

The potential impact of increased temperatures in the coastal environment has been considered for many years in the context of thermal pollution from power stations (Naylor, 1965) and there are some relevant data from a study of thermal tolerance of mangrove molluscs in Singapore (Hong & Chin, 1983). They concluded that several molluscs are living close to their thermal stress limits and that a 2-3°C temperature increase above the present ambient level would be detrimental to the mangrove ecosystem.

The potential impact of temperature change on bivalve-molluscs such as *Perna viridis* is likely to be particularly significant because being filter feeders, these animals are fully exposed to ambient water temperatures when feeding; also they have little or no ability to move to another shore location. Their only

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behavioral mechanism against temperature stress is to close their valves, but this can be achieved only at the expense of feeding opportunity and hence growth. Since mangrove bivalves include oysters, mussels, clams and cockles which provide important sources of food and income worldwide, (Quayle, 1980; Broom, 1985; McCoy & Chongpeepien 1988; Vakily, 1989), their response to temperature change has special significance to both the ecology and economic exploitation of mangrove ecosystems.

Mangrove gastropods, on the other hand, are mainly grazers or predators active at low tides when the mangrove habitat is exposed to air (Berry & Chew, 1973). Although unshaded areas can heat to extreme temperatures under such conditions, evaporative cooling seems to keep snail body temperatures much lower than ambient levels (Lewis, 1963). Mangrove crabs also use evaporative cooling for thermoregulation, as well as other mechanisms such as blanching (Edney, 1961; Smith & Miller, 1973).

In conclusion, it seems that soft bodied animals and bivalve molluscs would be highly sensitive to temperature rise, whereas the many species of mangrove crabs and gastropod snails could accommodate a hotter environment provided they had access to water to replenish water lost by evaporation, respiration, and feeding. However, climatic change which resulted in both temperature rise and greater aridity could adversely affect even snail and crab species, as could temperature rise coupled with more extreme salinity regimes. There is virtually no information to indicate what effect, if any, temperature rise would have on those animals more or less permanently resident in mangrove sediments or the soil meiofauna.

7.2. HYDROLOGICAL CHANGE AND MANGROVE FAUNA

Fluctuations in salinity are characteristic of mangrove environments and play a prominent role in regulating the presence of many animal taxa. The salinity regime of a mangrove swamp is the product of interactions between climatic factors (rainfall and evaporation rates), freshwater run-off, ground water influxes, coastal salinity regimes and current and tidal dynamics. The influence of these processes is moderated by local factors, such as shore gradient and topography, vegetation cover, soil properties and burrow-building by mangrove crustaceans, creating a wide range of salinity conditions, not only along and across the shore, but also at the micro-habitat level (Semeniuk, 1983).

In the equatorial tropics, surface salinities can drop to virtually zero during tropical rainstorms and rise to 50ppt if the habitat is exposed continuously to evaporation during neap tides (Sasekumar, 1970, 1974). Not surprisingly, the most common intertidal mangrove animals are euryhaline and many also have behavioural adaptations to reduce their exposure to salinity extremes and desiccation.

Mangrove shores are also inhabited by a few highly adapted species from animal groups normally associated with exclusively marine or freshwater environments. The Sipunculida, for example, a phylum of stenohaline marine worms regarded as lacking osmoregulatory ability, is represented in Asian mangroves by one species, *Phascolosoma arcuatum*, which can osmo-conform and maintain normal activity for many hours in salinities at least down to 40% that of standard seawater (Green & Dunn, 1976).

Although salinity tolerances have been worked out for only a few species of the intertidal mangrove fauna, available data suggest that moderate changes in salinity would not seriously restrict the distribution or activities of the principal groups. A likely scenario is that salinity changes would cause shifts in the relative distribution of species within those taxa containing mangrove animals occupying a halocline.

7.3. CLIMATE CHANGE AND MANGROVE-ASSOCIATED AQUATIC FAUNA

7.3.1. Mangrove Fisheries

Fish stocks and exploitable populations of crabs, shrimps and molluscs together make up one of the principal resources of mangrove ecosystems benefitting man. Relationships between mangroves and fisheries take several forms, both directly through habitat utilization by economic species and indirectly through energy and nutrient exports from mangrove shores into coastal waters (Macintosh, 1982). Even the mangrove trees themselves are widely exploited for fisheries purposes to provide materials for making fishing traps and cages, crab poles, lures, and many other fishing gear.

It has been estimated that small-scale fishing activities in mangrove estuaries and lagoons provide almost 1 million metric tons of fish and shellfish annually and generate work for about 1 million people

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(Matthes & Kapetsky, 1988). Actual yields are probably higher as much of the fishing within mangroves is of a subsistence nature and difficult to record statistically.

The ecological relationships between a mangrove and its associated aquatic fauna are the most difficult to research as the latter are generally free to move between different coastal zones (Hill et al., 1982; Chong, 1984; Robertson & Duke, 1990; Turner, 1992; Tzeng & Wang, 1992). Many species of fish and shellfish have distinct life stages with particular habitat preferences and move from habitat to habitat on time scales ranging from a single tidal cycle (Tzeng & Wang, 1992) to several months (Macintosh, 1982).

A useful inventory of economically important mangrove-associated aquatic species is provided by Matthes & Kapetsky (1988). Their distributions are divided into six zones within the mangrove ecosystem, extending from seaward sub-tidal areas to the inner zones of estuaries and river channels. The relationship of each aquatic species with mangrove ecosystems is also classified into one or more out of six categories: (a) fully dependent (i.e. whole life cycle); (b) eggs/larvae only; (c) fry/juveniles only; (d) adults only; (e) incidental; and (f) facultative (e.g. using mangroves as a migratory route).

7.3.2. Finfishes

Large numbers of fish species are associated with mangrove ecosystems for at least part of their life cycles (Austin, 1971; Austin & Austin, 1971; Odum & Heald, 1972). Individual studies in many mangrove locations have recorded more than 100 species from a given study site (e.g. Sasekumar et al., 1984; Robertson & Duke, 1990). In total, IUCN (1983) list almost 300 fish species from the mangroves of Asia and 100-200 species for the other main regions where mangroves occur (Table 3).

Habitat use of mangroves by fish is associated particularly with (1) nursery sites for juvenile stages of coastal fish species; (2) feeding areas for sub-adults of predatory fishes like snappers, sea-bass, estuarine groupers and marine catfish; and (3) the permanent habitat of small pelagic fishes, belonging chiefly to the families Leiognathidae, Clupeidae, Engraulidae, Centropomidae, Mugilidae, Gobidae, and Ambassidae (e.g. Robertson & Duke, 1990; Macintosh et al., 1991). Many species in these families feed within mangrove forests at high tide and have been shown to include mangrove detritus and/or mangrove fauna in their diets (Ong, 1978; Sasekumar et al., 1984). The larger predatory species mentioned above also browse heavily on mangrove invertebrates, as well as consuming smaller pelagic fishes (Sasekumar et al., 1984; Robertson & Duke, 1990).

Many studies have shown that mangrove ecosystems attract and support high densities of fish, especially the larval and juvenile stages of commercially important coastal species (Bell et al., 1984; Janekarn & Boonruang, 1986; Robertson & Duke, 1987, 1990). It follows that any components of climate change which adversely affect mangroves are likely to have harmful consequences on the recruitment of young fish into the commercial stocks. A net loss of mangrove area is therefore considered potentially devastating to certain existing fisheries (Kapetsky, 1985; Robertson & Duke, 1990).

7.3.3. Shrimps

Since the pioneering reports by Hall (1962) and Macnae (1974) suggesting a relationship between shrimps and mangroves, a large volume of information has been published showing the close association of many penaeid shrimp species with mangrove ecosystems. Several reports make quantitative assessments between the size and productivity of shrimp stocks and the areas of adjacent mangrove forests (Martosubroto & Naamin, 1976; Turner, 1977; Sasekumar & Chong, 1987; Primavera, 1991) or other wetlands (Morris et al., 1990; Turner, 1992).

Although tropical shrimps are not mangrove dependent in the strict sense, mangroves appear to provide a vital nursery environment for penaeid shrimp, giving them greater protection from predators and access to a rich food source, the latter principally derived from mangrove detritus and an associated biota of diatoms, meiofauna, bacteria and fungi (Macintosh, 1982). Studies along a mangrove-fringed coast in Malaysia have shown that an estimated 65% of the carbon assimilated by penaeid shrimps comes from the mangroves (Sasekumar & Chong, 1987). Shrimp occur in other coastal habitats, but the richness of the benthic food supply in mangroves is thought to explain their particularly high productivity in mangrove ecosystems. An example of the black tiger prawn, Penaeus monodon, is shown in Figure 5.
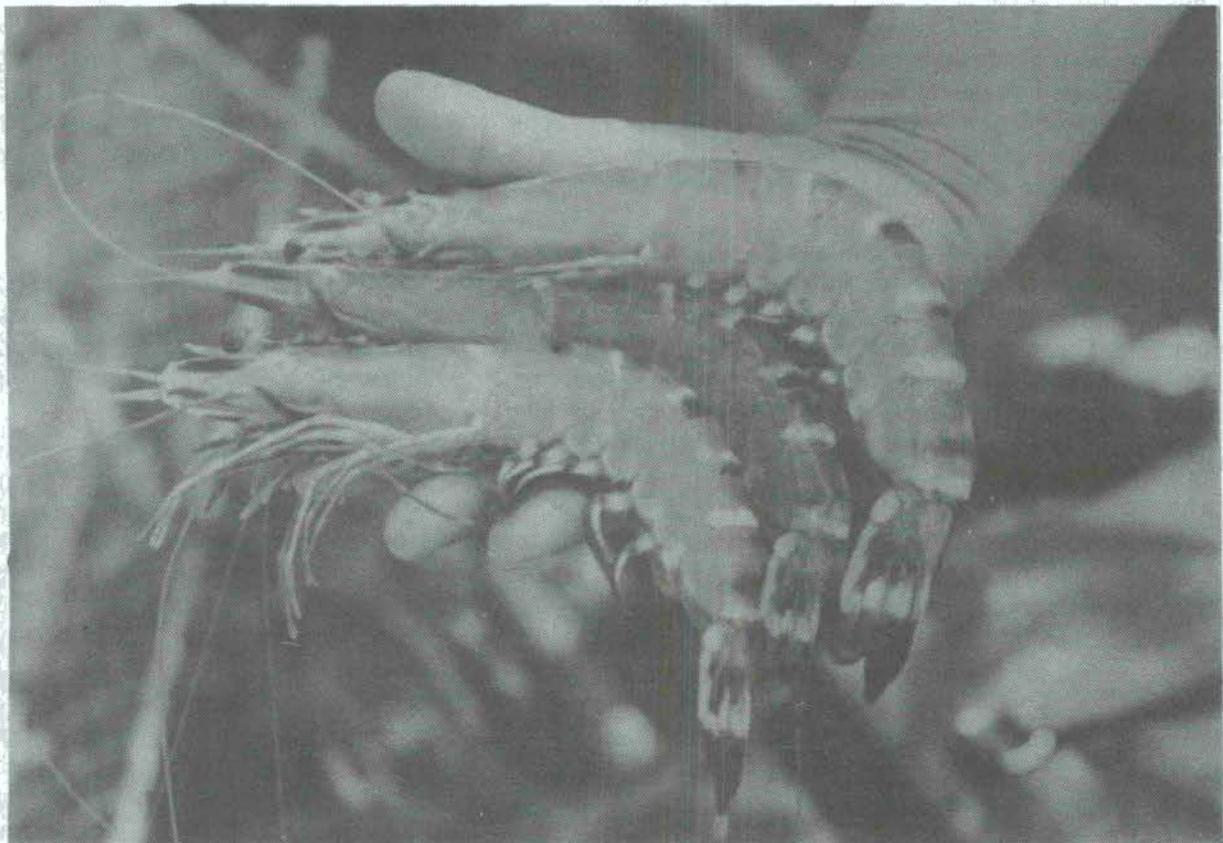
Figure 5: The black tiger prawn, *Penaeus monodon,* **a main shrimp cultured in mangrove aquaculture ponds (Photo D.J. Macintosh).**

It can be further concluded that the decline in shrimp stocks will correspond approximately to the relative decrease in mangrove resources. However, the mechanisms by which loss of mangroves may reduce shrimp stocks may be more complex than the assumption of direct loss of shrimp habitat. One example that can be quoted is the prediction of the consequences of erosion of mangrove areas in the Purari River delta (resulting from construction of a dam). Frusher (1983) concluded that the resulting decrease in sediment and organic matter into the inshore region of the Gulf of Papua would have a negative impact on shrimp stocks through decreasing the productivity of the substratum, which provides the food source for penaeid shrimps.

7.3.4. Summary of Climate Change Impacts on Fisheries

Climatic change can be expected to produce changes to many physical parameters in coastal waters, notably temperature, salinity, current and tidal patterns, wind speeds and direction, and possibly the strength of upwelling systems. Glantz (1992) has pointed out that the abundance and distribution of fish populations can be altered sharply by such changes, and by corresponding changes to other interacting aquatic species, such as predator populations.

Predicting and measuring the interactions between climatic change and mangrove fish stocks will be extremely difficult for two main reasons: (i) even in tropical latitudes there can be large scale natural fluctuations in fish populations; (ii) human fishing pressures in coastal ecosystems exert an artificial impact on mangrove fish populations, with changes in fishing effort obscuring and continuously modifying their response to natural events. In short, it is virtually impossible to predict accurately the future status of fish stocks because of the many variables that potentially are involved.

Although highly speculative, it seems reasonable to assume that the more physiologically adapted coastal fish and shellfish species will better survive the impact of climate change on mangroves, while more

specialized or less tolerant species may disappear. In mangrove ecosystems, where extreme and fluctuating salinities and high water temperatures are characteristic of the inshore environment, euryhaline and eurythermal animals like shrimps, crabs and certain finfishes such as mullets, tilapias and sea bass (*Lates calcarifer*) will proliferate. Since many fish groups are highly adapted to mangroves, there is no reason to presume a significant change in faunal taxa will result, although clearly the distribution and abundance of particular species will change as environmental gradients alter under climatic response.

It is concluded that small-scale fisheries typical of many tropical mangrove coastlines will be able to respond to the consequences of global warming much better than offshore industrial fisheries. The former are much more adaptable and diversified, require low investment in equipment and involve a wide degree of economic and cultural participation by local communities (Glantz, 1992). These features provide the potential for a high degree of flexibility and opportunism to respond to changing fishery scenarios resulting from any impact of climatic change on mangrove ecosystems.

Linkages between mangroves and inshore fisheries have been described. Of importance also are mutually supportive interactions between mangroves, seagrass beds and coral reefs; such that many authors consider these to be components of a coastal ecosystem complex, rather than separate systems (Ogden & Gladfelter, 1986). Physical, nutrient and biotic interactions at several levels have been identified within this complex; although these are poorly understood. Perturbation of the mangroves, resulting from climate change, is likely to disturb the stability, productivity and economic value of these neighbour components also.

8. IMPACT OF CLIMATE CHANGE ON LAND USE, UTILIZATION AND EXPLOITATION OF MANGROVES

Throughout much of the tropics the mangrove ecosystems sustain large human populations at subsistence levels. The mangrove ecosystem is valued for the extractable resources it supports, for the nonconsumptive services it provides and its intrinsic ecological value. Mangroves support diverse communities of fauna and flora of direct and indirect economic and social value to human societies. Fish stocks and exploitable populations of crabs, shrimps and molluscs make up the principal food resource. Timber extraction is also of great importance. Mangrove ecosystems provide a variety of nonconsumptive services including recreational and aesthetic benefits, protection from soil erosion, flood mitigation, filtering of nutrients and protection against saline intrusion.

It is well documented (Saenger *et al.*, 1983; Hamilton & Snedaker 1984; Field & Dartnell 1987) that mangroves are under constant development pressure because they are found in coastal and estuarine areas which are also centres of human settlement. Mangrove ecosystems are under extreme pressure from expanding populations and non-sustainable use, such as land reclamation for construction, agriculture and aquaculture. In the Insular Caribbean, coastal tourism development has been the main cause of mangrove destruction (Bacon, 1987). The basic question that arises in the management of a dynamic and complex ecosystem, such as mangroves, is under what conditions should it be maintained and managed for intrinsic value and when should it be reclaimed for alternative purposes. There have been only a few attempts to answer this question (Amarasinghe 1988; Milliman *et al.*, 1989; Lal 1990).

The consequences of possible global climate change have now to be added to an already unstable situation as far as mangrove ecosystems are concerned. It has already been shown that an enriched CO_2 atmosphere and a warmer and wetter climate would on balance favour the growth and expansion of mangroves. The major socio-economic problems are likely to be caused by the effect of rising sea level. The severity of these impacts will often be site specific and will depend, not only on the nature and extent of climate changes along different coastlines, but also on existing usage of mangroves and socio-economic conditions locally.

8.1 COASTAL PROTECTION

Existing natural and engineering structures (e.g. coastal embankments, sea dykes) that protect coastal land will be less effective against seawater intrusion, will experience greater storm damage, and consequently will require greater expenditures for repair and maintenance to support current levels of land protection. In some cases the maintenance cost/benefit ratio of existing protective barriers may necessitate

their relocation landward. Consideration should be given to the establishment of a mangrove green belt, where no such provision has already been made, to provide a natural barrier for coastal protection. There are now several examples of successful afforestation of coastal lands with mangroves (Qureshi, 1990; Saenger & Siddiqi, 1993). It would be useful if detailed guidelines and procedures for planting mangroves could be compiled so that in future there would be ready access to this knowledge when it is required. It would also be advantageous to train local people to have the necessary skills to afforest and reafforest coastal lands with mangroves.

8.2   AGRICULTURE

To the landward of mangrove systems, low-lying coastal areas presently utilized for agriculture (e.g. rice, oil palm, coconut palm, cashew nut, sugar cane) are likely to experience an increasing incidence of flooding by saline water, with a consequent increase in waterlogging and salinization. Such areas will become increasingly unsuitable for agriculture unless remedial measures, such as the construction of protective barriers, are taken. Where protective measures are not taken, it is likely that these areas will in time revert naturally to mangrove vegetation, which could serve as nursery grounds for coastal capture fisheries and as natural barriers for coastal protection, which might be utilized for the production of timber and other forest products.

In addition to the impact on existing agricultural activities in coastal areas, expected changes in climate and sea level will also affect the potential for future agricultural activities along the landward fringes of mangrove systems. In planning future agricultural activities in coastal areas, land use planners should take into account the possible effects of climate change on the likely economic lifespan of the development.

8.3   AQUACULTURE

Coastal aquaculture ponds are likely to experience a higher incidence of flooding, both tidally driven and storm induced. The impact of such flooding will vary locally, in most cases requiring modification of management practices, in others causing sufficient mortality of fishery stocks to jeopardize the economic viability of the ponds. This may necessitate relocation of ponds to more landward areas or the construction of additional barriers for protection. These barriers might take the form of engineering structures, the planting of a protective band of mangroves, or a combination of both.

Coastal aquaculture may also be adversely affected indirectly by reduction of mangrove ecosystem functions, leading to, for example, deterioration in water quality, or increase in coastal erosion rates.

The possibility of a rise in sea level and an increase in both the frequency and severity of tropical storms, means that new aquaculture projects should be sited in more landward areas where there is a lower probability of tidally driven or storm induced flooding over the projected lifespan of the project. It is further recommended that a protective barrier of mangroves be established and maintained to the seaward of aquaculture ponds.

Coastal aquaculture investments will be highly susceptible to alterations in the environmental conditions in mangrove ecosystems. Changes in temperature and salinity (both average and extreme) may alter the suitability of existing culture sites for production of particular fish or shellfish species. This will occur in one or more possible ways, when (a) conditions exceed the thermal or haline ranges for the species concerned; (b) the length of the growing season changes, or the growth rate is reduced, thereby probably making aquaculture operations less viable economically; (c) reproductive or recruitment dynamics of species change, thereby reducing the availability of juveniles to sustain aquaculture production. It is therefore recommended that growth rates of species in ponds and the recruitment of juveniles be monitored to detect early warnings of changes to which a response should be made. Whereas a reduction in the availability of juveniles to stock ponds could be offset by their increased production in hatcheries, other impacts due to climate change may necessitate modification of management strategies or relocation of ponds.

Raft and cage culture of shrimp, oysters, fish and other organisms may experience problems with turbidity or changes in haline conditions, while the culture of cockles and other benthic fauna may be adversely influenced by increasing instability of mudflats due to increased wave or storm activity. In both cases, it should be possible to relocate to more suitable sites.

8.4   COASTAL CAPTURE FISHERIES

Fisheries catches within and adjacent to mangrove areas will undergo change. The productivity of mangrove fisheries will probably increase within the first few decades because of greater erosion and mobilization of organic materials and nutrients from terrestrial sources, particularly where relative sea level also increases the areal extent of shallow water habitats within and adjacent to mangrove ecosystems. However, any benefits to fisheries productivity could be rapidly negated by corresponding increases in fishing pressure, or human destruction or pollution of mangrove habitats, including conversion to aquaculture ponds.

Overall, the impact of sea-level rise on mangrove ecosystems is likely to have a neutral or positive effect on fisheries, at least in areas where the size of the mangrove system is not reduced by increase in relative sea level. Conversely, processes which lead to loss of mangrove area or a reduction in freshwater flow, or which increase concentrations of suspended sediments and reduce dissolved oxygen in mangrove ecosystems, will have a negative effect on fisheries production.

Any reduction in coastal fisheries production as a consequence of climate change may have a significant adverse impact on the livelihood and well-being of dependent local communities. It would be advisable to monitor fisheries catches by local communities to detect early signs of changes in fisheries production in order to evaluate possible responses.

8.5   FORESTRY

The predicted changes in climate and sea level are expected to have significant site-specific impacts on existing mangrove forestry activities. The rate of forest growth and the yield of harvestable timber are both expected to decrease in those areas which experience an increase in aridity and / or an increase in salinity. Conversely, yields are expected to increase in those areas that experience a reduction in aridity and salinity.

Figure 6: Extraction of billets of mangrove wood for charcoal production, Kelang mangrove delta, Malaysia (Photo D.J. Macintosh)

An increased frequency and intensity of tropical storms, together with changes in wave activity is expected to alter present patterns of erosion and sedimentation, leading to the loss of some areas of mangrove now used for silviculture, and the creation of new habitats that might be suitable for plantation forests. Changes in coastal morphology should be monitored by countries in order to maximise the productive use of mangroves for silviculture and other forestry activities.

Changes in sea level or tidal range will affect the suitability of mangrove areas for silviculture through changes in soil water content, salinity and other soil properties. While these effects will probably be site specific, in general a rise in sea level is expected to reduce the suitability and yield of areas presently used for silviculture. On the positive side, some mangrove areas that are presently unsuited for silviculture are likely to become more suitable for the production of timber, charcoal and other forest products. In most cases, however, a rise in sea level is expected to reduce the number of rotations and the economic lifespan of silvicultural activities at particular sites. Forest managers and concessionaires should consider the merits of varying management practices (e.g. different planting densities and thinning regimes, and/or shorter rotations) to maximise yields over shorter periods of time. The extraction of mangrove wood for charcoal is shown in Figure 6.

Climate change is expected to affect the phenology of reproduction and growth. There is presently insufficient information to predict what these effects might be, or the extent to which they might be site- or species-specific. However, it should be noted that any loss in reproductive capacity could have a significant impact on the availability of propagules for plantation silviculture and reforestation, particularly in regions where they are already in short supply. Forest managers would therefore be advised to monitor the phenology of reproduction locally, focusing particularly on the production of viable, mature propagules. A loss of reproductive capacity locally may necessitate the use of propagules from areas which have not been affected, or the development of techniques for tissue culture of mangroves.

The scope and scale of these impacts will be directly proportional to the effects of climate change on specific commercial mangrove timber species, especially Rhizophora and Bruguiera species. If impacts are negative, serious economic losses can be anticipated, with associated implications for the livelihood and quality of life of affected coastal communities.

8.6   OTHER POLICY OPTIONS AND RESPONSES

Some specific policy options and responses to the possible effects of climate change have already been considered in sections 8.1 to 8.5. There are, however, a number of more general issues that will need to be addressed. Broadly, these additional policy options involve whether or not to relocate existing activities or human communities associated with mangroves, whether or not to implement an engineering solution, and the extent to which pre-planning of future activities can mitigate or avoid possible impacts of climate change on mangrove ecosystems and their dependent human communities.

In considering these matters and the possible economic results of any action, it must be stressed that the climate changes that may occur due to man-induced changes to the atmosphere are far from certain. The effects that predicted climate change may have on mangrove ecosystems are equally uncertain. The loss of economic resources which might occur as a result of climate change is extremely difficult to model or predict and will rely heavily on local factors. it is therefore wise to proceed with any response to possible climate change in a very cautious manner.

It must also be appreciated that changes taking place in the mangroves either due to natural causes or human activities may already be greater than might be expected from any predicted change of global climate. Examples of damage from natural causes are well documented such as devastation from cyclones, local sea-level rise, coastal erosion and flooding. Examples of human activities that disfigure and damage mangrove ecosystems include large conversions to fish ponds that in a few years exhaust the available nutrients and produce derelict land, land reclamation for port and urban development that converts beach front and produces soil erosion, mining activities that poison the surrounding environment and produce siltation of rivers and subsequent flooding, and deforestation and wood chipping that leave large areas of mangrove forest denuded and eroded. As these natural disasters and human misuses of mangrove ecosystems represent by themselves a major concern it is necessary now to devise policies and

management practices for the utilization of mangrove ecosystems and to include in these considerations an awareness of the problems that may result from the effects of man-induced climate change.

As the most likely effect on climate change on the mangrove ecosystem will be due to sea-level rise, an initial response is likely to be the construction of some form of barrier to the sea. On the whole, past engineering modifications to coastal environments have had mixed success, often creating secondary problems. They should, therefore, be used only when no alternative response is available or can be justified economically. Similarly, relocation of aquaculture ponds, agriculture and certain other forms of development may be feasible where there are suitable areas to the landward but in countries that have traditional land ownership rights in coastal areas, relocation of coastal communities and traditional activities associated with mangrove area may be difficult.

It cannot be stressed too much that governments should immediately establish a baseline data for their coastlines and mangrove ecosystems so that any change that may occur, for whatever reason, will be detected at an early stage. All future activities in mangrove areas and the hinterland to the landward of mangrove areas should be pre-planned with the probable impacts of natural climatic events, human activities and man-induced climate change firmly in mind, thereby minimising or avoiding any conflicts that may arise.

9.   HYPOTHESES TO BE TESTED

Changing climatic conditions are most likely to be manifested by average global increases in atmospheric CO_2, air and water temperatures, eustatic sea level, ultra violet radiation, storm frequency and magnitude, and possibly also by alterations in the present regimes with respect to cloud cover, rainfall, runoff, evapotranspiration, and salinity. It is assumed that the IPCC "business as usual" estimates of rates of change represent the most likely future scenarios (Table 4).

Based on the IPCC projections, an operational hypothesis has been adopted that climate change on time scales of decades will have an impact on mangrove ecosystems and that it will be possible to measure mangrove responses quantitatively.

Mangroves like most other ecosystems are complex systems with convoluted interactions and feedback loops. Mangrove ecosystems are therefore likely to exhibit synergistic responses to a combination of changing climatic parameters, making the analysis of specific causes and effects due to single factors such as temperature or sea-level rise extremely difficult. Also, the complexity and scale of responses will vary from one area to the next and be highly site specific.

All the hypotheses listed below are testable, but some can be more readily validated by interpretation of monitoring activities, whereas others may require more complex experimental study.

9.1.   INCREASING TEMPERATURE EFFECTS

Based on the IPCC scenario of a rise in air and water temperatures of 0.3°C per decade (Table 4), it is hypothesized that:

(a)   A number of mangrove species will migrate towards higher latitudes in response to temperature increase in areas where ocean currents are favourable for propagule dispersal, thus increasing the prevalence and importance of mangroves as a coastal ecosystem. The extent of geographical progression is likely to vary in different parts of the world, but be particularly pronounced along eastern continental margins. This migration by mangroves will require more than four decades to become significant.

(b)   Changes in seasonality will result from these predicted temperature increases, with the growing season for mangroves becoming longer. This will alter the phenological patterns of reproduction and growth in many mangrove species.

(c) On a global basis, overall net and gross productivity of mangrove ecosystems will increase as a result of the temperature increase. The increase will be proportional to the change in areal extent mangroves.

(d) Primary productivity per unit area will increase in the aquatic zone through higher rates of photosynthesis by phytoplankton and faster rates of microbial breakdown of detritus, but primary productivity per unit area will probably decrease in mangrove forests due to increased rates of root respiration, root death, and root replacement, which are expected to result from a rise in mean soil temperature.

(e) Plant and animal biodiversity will increase and mangrove plant and animal composition and distribution will change. Changes in distribution and abundance of the resident mangrove fauna will reflect primarily responses to climatically induced changes in the mangrove vegetation community, especially the degree of ground cover and structural changes.

(f) Extensions in the range of mangrove vegetation will be followed rapidly by colonization of new mangrove areas by faunal-associates, a conclusion supported by the high dispersal capabilities of the many mangrove animal species which have planktonic larval stages or aerial abilities.

(g) Reproductive seasons, respiration, and growth rates of some mangrove animals will respond to temperature increase, with consequent alterations in their population dynamics (e.g. fecundity and recruitment rate, and population production and turnover rates)

(h) Eurythermal and/or behaviourally adaptable animals, such as mangrove brachyuran crabs, gastropod snails, and mudskippers will cope better with temperature rise than other taxa.

(i) Mangrove microbial processes will accelerate because of higher rates of organic decomposition and nutrient recycling. However, the latter may be moderated by any decline in mangrove primary productivity. Changes in microbial processes will have a measurable impact on the productivity of secondary consumers, including heterotrophic bacteria, meiofauna and macrofauna, including aquatic species of economic value.

(j) A rise in mean soil temperature will increase root respiration and root turnover, which will cause an increasing drain on the carbon resources of mangrove trees and associated vegetation, that may result eventually in substantially reduced growth rates.

(k) A rise in mean air temperature will have only a marginal impact on the photosynthetic-respiratory balance of mangrove leaves, but it is likely to increase stem respiration. These effects will be small however, compared to the impact of rising soil temperature.

9.2. WATER BALANCE RELATED EFFECTS

The effect of temperature change on mangrove ecosystems is also intimately tied to the availability of fresh water. The water balance will respond to climate change but will vary regionally and locally without a fixed global pattern. Local changes in rainfall, evapotranspiration, runoff, water and soil salinity, and degree of cloud cover control the water balance and will impact promptly on the structure and function of the mangrove ecosystem. It is known that photosynthesis and growth by plants are primarily contingent on temperature, climatic aridity, and salinity.

Thus, it is hypothesized that:

(a) An increase in the precipitation to evapotranspiration (P/ET) ratio will result in an increased rate of primary productivity by mangrove plants.

(b) If climate change causes more pronounced seasonality in the P/ET ratio, mangrove primary productivity will decrease during periods of negative P/ET ratio.

(c)   An increase in soil salinity, brought about by the balance between salt water intrusion and runoff, will reduce mangrove plant primary productivity and growth rate; conversely a decrease in salinity will enhance mangrove plant primary productivity and growth rate.

(d)   A permanent decrease in the P/ET ratio, or more pronounced seasonality in the P/ET ratio, is likely to increase the abundance of evaporite minerals, hypersaline groundwater, and abundance and expanse of salt flats along the landward margin of the mangrove systems, which in turn will restrict landward progression of mangroves in response to relative sea-level rise.

(e)   Mangrove animals, which are euryhaline, or which can adjust behaviorally to environmental change, will be unaffected by all but extreme salinity changes. In contrast, the distribution of stenohaline species may be altered significantly by salinity change. Greater freshwater influx will favour groups with a terrestrial or freshwater origin, while increased saltwater intrusion and evaporation will favour marine species.
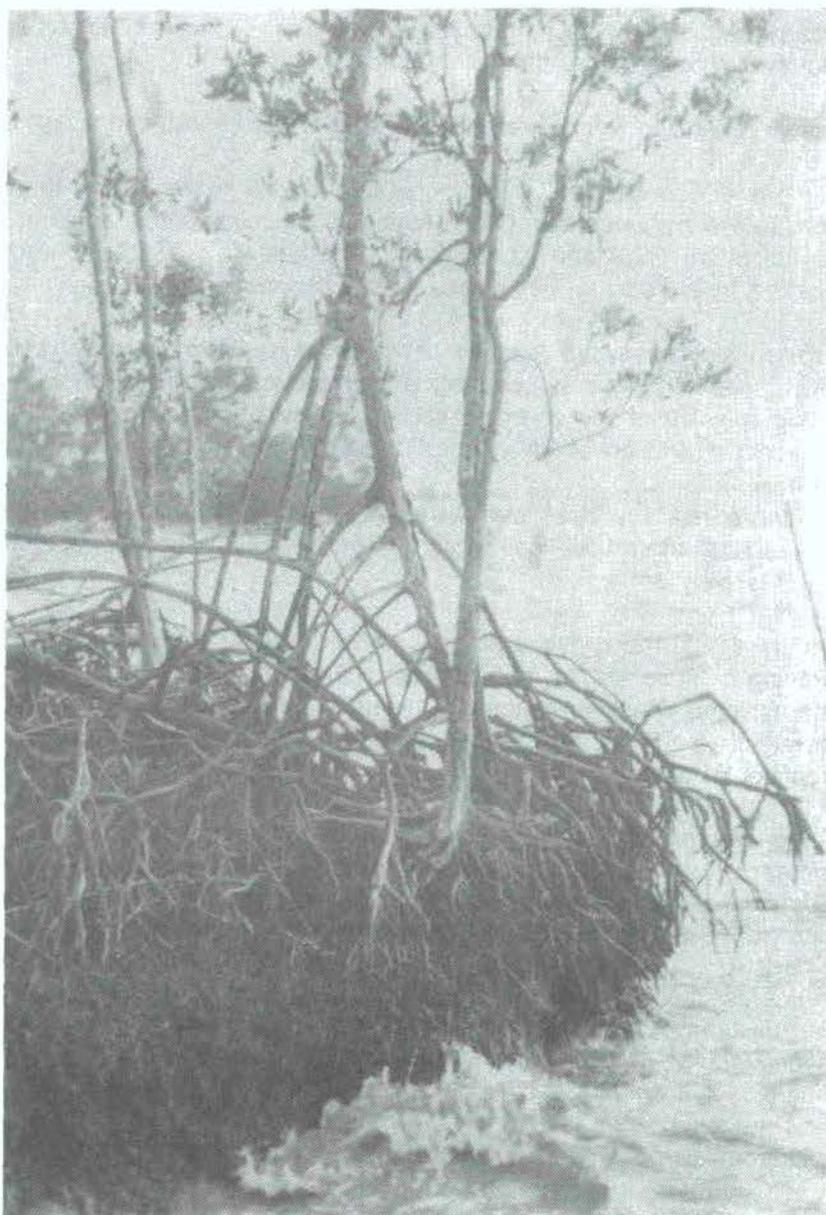

Figure 7: Erosion of *Rhizophora* **mangrove forest in Port Klang, Malaysia due to coastal development (Photo D.J. Macintosh)**

(f)   The upstream penetration of mangrove-associated aquatic animals will change significantly in relation to shifts in the seawater-freshwater balance in estuaries, deltas, and lagoons. A greater freshwater intrusion will extend the inshore distributions of important euryhaline stocks, especially postlarval and juvenile stages of penaeid shrimp, whereas more marine dependent groups, such as many crab larval stages and the young of coastal pelagic fish species will be more inhibited in their upstream penetration. The reverse will occur in deltaic-estuarine locations where saltwater penetration into mangrove ecosystems is increased.

9.3.   RISING SEA-LEVEL EFFECTS

Whereas the eustatic sea level will rise during the foreseeable future, the relative sea level may either rise or fall locally or regionally, depending on prevailing natural and anthropogenic factors (Stewart et al., 1990). Relative sea-level rise is more common than relative sea-level fall, especially for mangrove systems located in delta areas and along trailing-edge coasts. The rate of relative change may be up to nine times greater than the IPCC "business as usual" eustatic increase in delta areas because of sediment compaction (Milliman et al., 1989). Thus, in any study location, it is necessary to base hypotheses on the relative rate of sea-level change rather than on eustatic change.

In locations experiencing relative sea-level rise, it is hypothesized that:

(a)   Mangrove communities will progress landward in response to rising sea level, until constrained by natural relief and existing dikes, bulkheads, roads, other man-made barriers, or agriculture fields and urbanization. The landward migration of mangroves will also be blocked by increasing dimensions of salt flat areas.

(b)   Erosion along seaward margin of mangrove systems will occur in response to rising sea level and storm events, causing a net loss of mangrove area along coastlines where topographic relief or man-made barriers constrain landward progression of mangroves. An example of erosion of Rhizophora mangrove forest is shown in Figure 7.

(c)   If relative sea level rises at a faster rate than the mangroves can move landward, or at a faster rate than they can grow, trees of each successive generation will become progressively smaller.

(d)   Provided that mangrove areas are not reduced, the available shallow-water nursery and feeding habitats for fish and shellfish will probably increase in size as additional areas of the adjacent coastline become submerged as a result of relative sea-level rise. This may be significant in areas bordered by shallow epicontinental seas or broad, gently sloping continental shelves.

(e)   Secondary productivity per unit area within and adjacent to mangrove systems will probably increase with rising relative sea level due to increased erosion, greater availability of nutrients, and increased primary productivity; this in turn will have a positive effect on secondary aquatic production, including fisheries.

(f)   Nutrients, organic matter, and contaminants stored in the mangrove sediments are likely to be released during episodic storm, runoff, or tidal events, and depending on the rate of sedimentation, this may either enhance nearshore productivity or cause rapid burial of fresh and recycled nutrients and organic matter, which could lead to inhibition of benthic mixing and removal from the biological cycles of nutrients and organic matter, resulting in oligotrophication.

(g)   Soil acidification is likely to occur due to oxidation of FeS to sulphuric acid from increased erosion of mangrove muds as relative sea level rises.

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9.4. INCREASING CARBON DIOXIDE CONCENTRATION EFFECTS

Most evidence suggests that photosynthesis and growth are limited primarily by extremes of salinity, temperature, and climatic aridity. Atmospheric CO_2 levels do not appear to be significant in directly limiting photosynthesis or growth. Consequently, the predicted rise in atmospheric CO_2 level is not expected to lead to a significant increase in mangrove forest canopy photosynthesis. However, it is hypothesized that:

(a) Increasing atmospheric carbon dioxide levels will assist mangrove trees to control more effectively their water balance and reduce water stress, thereby affecting growth.

(b) There will be significant species variation in the response to elevated CO_2.

9.5. INCREASING TROPICAL STORM EFFECTS

Tropical storms (including hurricanes in the Atlantic, typhoons in the Pacific, and cyclones in the Indian Ocean provinces) occur over oceans and seas fringed by mangrove wetlands, and these mangrove fringes serve as a protective barrier against storm damage for human habitats and structures. Where tropical storms make landfall, it is inevitable that mangrove ecosystems will be affected by these events. It is therefore hypothesized that:

(a) Mangrove coasts will be impacted more frequently and with greater impact by tropical storms as a result of climatic change, thereby putting human activities and resources at greater risk.

(b) The impact of tropical storms on tropical and subtropical coastal resources will be less catastrophic in areas with well developed mangroves than along coasts lacking in mangroves or with significantly degraded mangroves.

(c) Mangrove ecosystem productivity will be enhanced as a result of exposure to greater tropical storm frequency because of influx of nutrients and material resuspension, provided that the structural and vegetative integrity of the mangrove community is not destroyed by the intensity of the associated wind and wave action.

10. MONITORING AND STUDIES IN MANGROVES

10.1. RATIONALE FOR MONITORING AND STUDY

The rationale for monitoring and studying mangrove ecosystems to determine the effects of predicted climate change is that mangrove ecosystems are likely to be one of the first ecosystems to show changes due to climate change and the effects may have great significance for the economic well being of the large coastal population in the tropics. A discussion of the types of monitoring and specific studies and experiments that need to be undertaken to test the above hypotheses, including an evaluation of the frequency and duration of measurements, was outlined by UNEP/UNESCO (1992a). The preparatory meeting concluded that the effect of changes in climate might be most pronounced in those places where the mangrove ecosystem was close to the extremes of its distribution and that it might be easier to detect change in systems that are currently relatively stable.

Mangrove ecosystems are inherently dynamic and if the rate of natural change is too rapid it might be difficult to detect trends that are occurring as a result of global changes in climate. In order to narrow the scope of studies to reasonable proportions, it was recommended that at least three representative types of mangrove ecosystem be examined: (a) well developed deltaic sites, (b) sites along arid coasts, and (c) low island sites.

The objective is to design a long-term monitoring and study programme that can be implemented at a small number of primary sites or long-term and intensive studies, together with additional secondary sites for the gathering of complementary information covering a wide geographical distribution of sites.

10.2. STUDY SITES AND PREREQUISITE SITE INFORMATION

The following is a summary from UNEP/UNESCO (1992a) of site requirements for mangrove monitoring and studies related to expected climate change impacts.

Primary sites should be already well documented and have relevant information and time series data available, such as meteorological records, species composition, geomorphology, and sea-level change, to achieve optimal use of resources. They should be also representative of the three principal types of mangrove site defined above. As far as possible they should be free of anthropogenic interference.

At each selected primary site, a parallel training programme should be enacted to provide protocols with respect to acquisition, analysis, and interpretation of data. This will encourage the sustainability of long term acquisition of accurate field data and their local use. The training programme will not only provide the site-based technical personnel with the necessary knowledge to carry on monitoring activities and studies, but will also help the staff to make appropriate decisions when unpredictable events affect monitoring and study activities at the site.

Detailed methodology at each primary site will be site specific and will be fully defined once the sites have been designated. The findings from the primary sites will be used to modify the approaches used at the secondary sites in time.

Secondary sites are additional mangrove monitoring and study sites to complement the existing diversity and geographical distribution of mangrove habitats. These sites are selected to complement monitoring and study activities and results obtained at primary mangrove sites, and to provide comparable local information with a wide geographical distribution. It is not necessary that the full UNEP/UNESCO-recommended monitoring and study programme be established at each secondary site. Activities could rather consist of selected monitoring and study activities as a means of complementing or comparing data or results obtained at primary sites. The degree of implementation of any programme activity at secondary sites would ultimately depend on the availability of funds and resources. Secondary sites could be selected from among mangrove sites around the world, where studies are in progress.

It is important to organize a reliable system for monitoring and study of data for at least several decades. The data should not only be used for assessing the impact of climate change on mangrove ecosystems, but should also serve more immediate local needs in examining and managing local environments. It is equally important to design associated experiments and modelling exercises at the primary sites, and to analyze optimally the data collected from the monitoring programme. It should always be remembered that modifications to mangrove ecosystems due to climatic change may be very difficult to discern from modifications due to anthropogenic actions and episodic natural events. Experimental design should be evaluated carefully with consideration given to such complications.

The preparatory UNEP/UNESCO Task Team meeting (UNEP/UNESCO, 1992a) suggested that as a prerequisite to selecting a mangrove site and measuring parameters at the site, it is necessary to:

(a) Select an appropriate geomorphological unit with a well developed mangrove system to serve as a study site.

(b) Select a study site, where the evolution of the site has already been well studied with the existence and availability of extensive data sets, aerial photographs, satellite images and meteorological information.

(c) Construct a base map of the mangrove site in a geographical information system (GIS).

(d) Establish the location of the most adjacent GLOSS tide gauge network site and the availability of high-quality water level data from this location.

10.3. PARAMETERS TO BE MONITORED AND STUDIED

Considerable attention has already been given to the measurement of parameters of importance to mangrove ecosystem functioning (UNDP/UNESCO, 1986; UNEP/UNESCO, 1992a, 1992b). It is not the objective of this report to design the optimum monitoring activities, in-depth studies, required experiments, and modelling exercises, as this will require considerable additional planning, and has funding and resource implications.

However, in developing the studies and monitoring activities, it is vital that careful consideration be given to (a) historical data for the site; (b) how the parameters and processes should be measured; (c) which of them are most appropriate for monitoring, for in-depth studies, experimentation, and modelling; and (c) the assessment of the technical feasibility (reliability of measurements; accuracy of data; manpower needs; equipment requirements; analytical capabilities; degree of difficulty in conducting field work, experiments, and modelling; and costs in relation to available funding). It is also important that all the sites be joined into a scientific network with comparisons between site data conducted on a regular basis.

Parameters and processes that should be included:

(a)   Digital Geographical Information System (GIS) Global Mangrove Map: it would be useful to construct a GIS and the following digital data layers would be required:

- coastline and extent of mangroves at mean sea level
- river and waterway boundaries at mean sea level
- topography and bathimetry
- land cover, and, where possible, vegetation types
- soil type and, possibly, soil salinity
- roads, power lines, transmitters and sewage ducts
- human settlements
- flow boundaries, barrages and barricades

When convenient Landsat, MSS or Spot satellite images or scanned aerial photographs can be overlaid on to the digital data planes. Documentation of the ground truthing is always required.

(b)   Rate of relative sea-level change: determinations are required to assess trends and variability of local relative sea-level change on a variety of time scales. The analysis of the data should be used to distinguish global and local variations. This requires continuous, long-term water level measurements on at least an hourly basis from a local tide gauge for which a stable vertical reference datum exists (IOC, 1985; Pugh, 1987). The data needs to be analyzed in comparison with the water level data from the most adjacent GLOSS tide gauge.

(c)   Rate of sedimentation or erosion: previous studies should indicate the long-term sedimentation rates from C^{14} dating of stratigraphic cores. Recent sedimentation rates can be monitored by a number of techniques:

- use of Pb^{210} or Cs^{137} isotopes in shallow stratigraphy (Lynch et al, 1989). This is the best technique but expensive.

- use of exotic markers such as feldspar clay is possible in mangroves where sedimentation is largely organic.

- insertion of a calibrated stake into the sediment requires basal fixation, otherwise it is lifted by below ground production and does not record sedimentation. Results can be unreliable in the short term (Spenceley, 1982), so measurements should be made every five years. Inserted stakes are the best technique to determine erosion.

(d)   Topography and bathymetry: determinations should be made of the mangrove site to assess elevation and depth distributions on a sufficiently fine scale to identify micro-topographic features with a vertical resolution of the order of 5 cm, referenced to the vertical site and tide gauge reference datum. Elevation of the substrate surface can be surveyed in detail by use of electronic

distance measurement (EMD) techniques and, where appropriate, liaison with government survey departments is suggested. In some cases water level can be used during the survey as described by Ellison (1993) and is useful in areas inaccessible to EDM.

The site topographic and bathymetric determination can be geo-referenced using GPS satellites and altimetry. Benchmarks should be established around the mangrove areas to allow reference between surveys over time.

(e)   Quality of deposited sediments: if sedimentation or erosion equilibrium is altered as a result of climate change, there will be changes in the physical and chemical characteristics of sediments, including grain size, mineralogy, composition, texture, salinity, total carbon content, sulphur content, nutrient dynamics, and detritus production. It may be difficult to measure the changes in nitrogen, phosphorus and trace metals as they are a function of many variables and would be difficult to monitor.

Apart from soil parameters it may be useful to measure CO_2 and H_2S flux from the sediment as a measure of the metabolism of the sediment. Basic soil components can be analyzed using standard techniques. The frequency of such determinations should be annual or biannual and the sampling sites should be selected to include the major community types or topographical features typical of each site. CO_2, H_2O and salinity determinations should be performed more frequently to determine seasonal patterns.

(f)   Climatology: it is important to perform continuous measurements and regular analysis of rainfall, temperature, humidity, solar irradiance, evapotranspiration, and wind speed and direction at a fixed sampling rate, ideally hourly but possibly less frequently. A minimum of one location within the mangrove site should be established, preferably close to the seaward margin from a site unobstructed by trees and buildings in accordance with standard meteorological measurements. Also records should be made of the path, time and central pressure of tropical storms, where the centre of the storm passes within 300km of the mangrove site.

(g)   Hydrology and Oceanography: it is necessary to make continuous measurements and regular analysis of runoff from main rivers that impact or flow into the mangrove site on a daily basis. The river site should be sufficiently upstream such that it lacks tidal water level variability. Other determinations should include continuous measurements of water temperature, salinity, and water turbidity on an hourly basis at a fixed site in a major water way, near the seaward margin of the mangrove site; continuous measurements of significant wave height and wave period every three hours at a fixed site in the open ocean seaward of the mangrove site, where the water depth is at least 10m; continuous measurements of water level variations on an hourly basis from a tide gauge at the mangrove site, for which a stable vertical reference datum exists (NOS/NOAA, 1976; IOC,1985; Pugh 1987).

(h)   Mangrove forest structure and function: changes in sea level or other climatic conditions are expected to influence growth rate, mortality, reproductive capacity and seedling recruitment in mangrove ecosystems. Any effect of climate change on forest structure, recruitment and mortality of mangrove trees is expected to take at least several decades to detect. Furthermore, measurements of stem diameter are seldom precise enough to provide reliable estimates of growth rate in more mature, natural mangrove forests over intervals of less than 5 years, although the reliability of such estimates from changes in stem diameter in rapidly growing plantations is somewhat better. Because of this imprecision, the expected rate of climate change, and changes in the age and population distributions of mangrove forests with time, it will be extremely difficult or impossible to distinguish between the effects of climate change on the growth rate of individual trees and the effects of other impacts unrelated to climate change. Nevertheless, it is recommended that permanent plots be established at selected sites to monitor long-term changes in forest structure, recruitment and mortality.

The earliest signs of an impact of climate change on mangroves themselves are likely to be seen in the canopy, in part because leaves have a relatively short lifespan (usually 1-2 years) by comparison with most other parts of the tree. In addition, field observations and experimental ecophysiological studies indicate that leaf morphology and the rates of leaf production and

senescence are sensitive indicators of climatic conditions such as temperature, irradiance, cloud cover and rainfall, and of soil conditions such as soil salinity, soil water content and other soil characteristics, which are likely to be altered by changes in sea level and climate. A monitoring programme to detect an early impact of climate change on mangroves should therefore focus on measurements of key canopy characteristics or processes that are expected to respond to climate change. It is recommended that these measurements be made within the same permanent plots that are used to monitor changes in forest structure. Concurrent monitoring of meteorological parameters, sea level, sedimentation rate, and other physical parameters is essential in order to correlate biological indicators with climate changes.

A programme to monitor the impact of climate change on mangrove vegetation should include the following aspects:

■ Forest structure: changes in forest structure should be monitored using replicated (at least 3) permanent plots in different types of mangrove forest located, in most cases, along a transect line from the seaward and landward margins. Descriptions of where and how to establish plots, and of techniques for monitoring the impact of climate change on community structure may be found in Anonymous (1986, 1993).

■ Leaf production, morphology, growth and senescence: the ratios of the area of a mangrove leaf to both its dry weight and its thickness are inversely correlated with thermal stress and water stress. In general, leaves which experience thermal stress or water stress (which are closely inter-related) are thicker and have a greater dry mass per unit leaf area than those which do not experience these stresses. Furthermore, in many species of mangrove, particularly members of the family Rhizophoraceae, thermal and water stress induces curling of the leaf margins, often with a marked reduction in the size of the leaves.

Rates of leaf production, growth and senescence, as well as changes in leaf morphological characteristics can be measured very simply, using little more than a ruler, callipers and an oven. Measurements should be made annually at the same time each year to minimise seasonal variation. They should be made on tagged rosettes or small branches (depending on the species) near the top of the canopy or in exposed positions on the trees.

Non-destructive measurements of leaf growth can be made by tracing the outline of leaves onto paper, or making an image of the outline of the leaf on light-sensitive paper, and then, in either case, measuring the area with a manual or electronic planimeter. Alternatively, reliable estimates of leaf area in many species can be obtained by linear measurement of length and breadth. In this case it is first necessary to establish a relationship between the linear dimensions and leaf area by measuring the length, breadth and area of a large number of leaves of different sizes for each species.

While measurement of the ratio of leaf area to leaf thickness can be made non-destructively in the field, the measurement of the ratio of leaf area to leaf dry weight requires destructive sampling. These measurements should therefore be made on a different set of rosettes or branches to those used to monitor leaf growth and senescence. Unfortunately, there are no well-established and published procedures for these kinds of measurements.

■ Reproductive capacity and phenology: the timing of flowering and fruit set of some mangrove species is strongly seasonal. Furthermore, high levels of predispersal mortality have been observed in several species of *Rhizophora* that are used widely for silviculture. Reproductive phenology and success are expected to be sensitive indicators of climate change and should therefore be monitored.

There are no well-established methods for monitoring phenology. Experience suggests that it is best to tag shoots where possible and maintain detailed records of the time of appearance and numbers of reproductive structures at the following stages of development; appearance of flower buds, anthesis, fruit (propagule) formation, mature propagules. Phenological studies have been reported by Christensen & Wium-Anderson (1976),

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Konsangchai *et al.* (1982), Konsangchai & Havanond (1985), Gill & Tomlinson (1969), Tomlinson *et al.* (1979), Chai (1982) and Aksornkoae *et al.* (1991).

(i)   Mangrove microbial and meiofauna communities: studies are required of distribution, abundance, and community structure of soil microbes (especially bacteria) and meiofauna (especially nematodes and protozoans) in relation to soil geochemistry, topography, tidal parameters and climatic parameters. The role of microbes and meiofauna in mangrove decomposition and as a food source for secondary consumers should also be examined.

j)   Mangrove intertidal and aquatic fauna: studies are required of growth rates and breeding patterns of key animal and fish species on an annual basis, where growth rates can easily be estimated for sessile animals with shells (e.g. oysters, mussels) but are more difficult for fish, shrimp and crabs. The methods for study of reproductive cycles and productivity are well established (Macintosh, 1986; Broom, 1985). The effect on fisheries might be determined by measuring the areal changes in the extent of mangroves and delineation of those areas which represent nursery sites for fish/shellfish; monitoring of fish/shell fish landings in neighbouring communities; and collecting and analysis of data on changes in catch rates, quantities landed; fishing methods, species caught, catch per unit effort, and fishing pressure.

11. CRITERIA FOR SELECTING MANGROVE STUDY AND MONITORING SITES

The selection of suitable sites for long-term study and monitoring to assess climate change impacts on mangrove ecosystems should be done with extreme care to ensure the selection of the most appropriate locations. These should enable detection and efficient recording of environmental impacts resulting from climate change in as short a time as possible, and where changes due to anthropogenic actions readily can be detected and separated from climate change impacts. This selection process will not be an easy task. Also, because of funding and resource constraints, only a small number of primary mangrove sites can be expected to be included in the programme.

In selecting primary or secondary mangrove sites for inclusion in the UNEP/UNESCO monitoring and study programme to assess climate change impacts on mangrove ecosystems, it would be wise to build on the extensive experience gained during execution of the now completed UNDP/UNESCO Regional Mangrove Project for Asia and the Pacific, especially the Second Phase Pilot Programme of Survey and Research on Mangroves in Ranong, Thailand, 1986-1990 (UNDP/UNESCO, 1986). As a consequence of this project, there now exists a keen awareness of the value to society of mangrove ecosystems in the Asia-Pacific region. Moreover, the community of mangrove specialists developed through this programme has acquired the experience of working together effectively, and is formally linked to relevant governmental services through national mangrove committees (NATMANCOM).

The International Society of Mangrove Ecosystems (ISME) is a lasting outcome of the UNDP/UNESCO Regional Mangrove Project for Asia and the Pacific, and is currently sponsoring mangrove inventories in Asia, Africa, and Latin America in cooperation with the International Tropical Timber Organization (ITTO). The country reports resulting from these inventories should be consulted in the process of selecting suitable mangrove study and monitoring sites for the current UNEP/UNESCO programme.

The experience gained in selecting the Ranong mangrove study site for the UNDP/UNESCO Regional Mangrove Project for Asia and the Pacific, provided the basis for developing guidelines and criteria for selection of primary and secondary mangrove monitoring and study sites under the auspices of the current UNEP/UNESCO programme. The criteria for site selection are:

(a)   Site Characteristics: A mangrove study and monitoring site needs to be a logical, intact, stable, geomorphic unit, preferably an entire watershed or a portion of the watershed which can be considered separate from the whole, and which is situated within a protected area, such as a park, conservation area, or biosphere reserve. The sites for consideration should be as pristine as possible, representing environments with minimal past, present, and future human influence. Whereas it may be unavoidable to select sites with human habitation, it is desirable that the

population density is low to ensure minimum future human impact on the mangrove system. Both the history of past environmental management and the long-term development plan of a mangrove study and monitoring site should be well known. The bulk area of a site should support mature mangrove trees, preferably 30 years and older.

(b) Site Area: The ideal size of an experimental mangrove area depends on whether the unit is a humid delta site, an arid site, or a low island site. For a delta site, the selected mangrove unit should represent a logical unit with respect to the local watershed and ideally cover at least 5,000 ha. For an arid site, the area should ideally measure 1,000 ha or more. For a low-island site, it is not possible to specify a minimum area, recognizing that many islands are very small.

(c) Data Availability: It is highly desirable that selected mangrove monitoring and study sites have already had an inventory, that accurate maps and charts exist, and that air photographs and satellite images covering the site are also in existence. The pre-existence of annual records of climatic, meteorological, tidal, and hydrologic site data is also highly desirable. The existence of vegetation cover, soil type, and other geographical information system (GIS) type maps of the mangrove site would be beneficial too. The site history with respect to anthropogenic influence must be well known.

(d) Government Approvals: A prerequisite for selection of a mangrove site for study and monitoring is an official invitation and endorsement, as well as information on arrangements, by national, district, and/or local government institutions and administrators for managing the site. A keen interest and a positive long-term commitment by institutions, administrators, including local site administrators and personnel, should be a positive consideration in site selection.

(e) Institutional and Personnel Support: It is highly desirable that a mangrove site for study and monitoring has dedicated institutional scientific and management staff on site, or conveniently, to ensure routine supervision of the study area; continuity in execution of routine monitoring, data collection, and data analysis activities; availability of laboratory and scientific institutional support for preliminary analysis of samples and data; and local security arrangements adequate to ensure the personal safety of individuals carrying out monitoring and study activities.

(f) Data Base: Arrangements must exist, or be instituted, to ensure that all data from a mangrove study and monitoring site can be processed and entered into a computerized scientific database in a routine fashion for sharing of information. Arrangements must also exist, or be instituted, to ensure that all site data can and will be made publicly available upon request. The willingness to allow all site information and data to be analyzed and published in a timely fashion, either jointly or with the cooperation of the on-site institutional staff is a necessary prerequisite. It is highly desirable that a government coordinating body, possibly a national mangrove committee (NATMANCOM), formalize and control data sharing and data distribution arrangements.

(g) Infrastructure: Mangrove sites for monitoring and study need to have in place local site infrastructure, or the willingness and means to install the required infrastructure, including basic facilities for accommodation, field work, and laboratory analysis; accessibility to site locations, including boat transport; arrangements to ensure personnel safety; and monitoring equipment and a programme for its maintenance.

(h) Training and Education: An essential ingredient to the long-term success of a mangrove climate change programme and a prerequisite for selection of a mangrove site for study and monitoring is the existence of an in-country commitment to education and training of local young scientists. There must also be in existence an implemented plan and the means to support the long-term involvement of local young scientists in the mangrove site study and monitoring programme.

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13. ACRONYMS

COMAR	Coastal Marine Project, UNESCO Major Interregional Project on Research and Training Leading to the Integrated Management of Coastal Systems
FAO	Food and Agriculture Organization of the United Nations
GLOSS	Global Sea-Level Observing System
GOOS	Global Ocean Observing System (IOC/UNEP/WMO)
IDRC	International Development Research Centre (Canada)
ICLARM	International Centre for Living Aquatic Resources Management
ICSU	International Council for Scientific Unions
IGBP	International Biosphere-Geosphere Programme
IOC	Intergovernmental Oceanographic Commission of UNESCO
IPCC	Intergovernmental Panel on Climate Change (WMO/UNEP)
ISME	International Society for Mangrove Ecosystems
ITTO	International Tropical Timber Organization
IUCN	World Conservation Union
SCOR	Scientific Committee on Ocean Research
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USDA	United States Department of Agriculture
WMO	World Meteorological Organization

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