Hydrobiologia **295**: 75–81, 1995.
Y. S. Wong & N. F. Y. Tam (eds), Asia-Pacific Symposium on Mangrove Ecosystems.

Impact of expected climate change on mangroves

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Key words: climate change, mangrove, ecosystems

Abstract

There is a consensus of scientific opinion that the activities of man will cause a significant change in the global climate over the next hundred years. The rising level of carbon dioxide and other industrial gases in the atmosphere may lead to global warming with an accompanying rise in sea-level. Mangrove ecosystems grow in the intertidal zones in tropical and sub-tropical regions and are likely to be early indicators of the effects of climate change. The best estimates of predicted climate change in the literature are presented. It is suggested that a rise in mean sea-level may be the most important factor influencing the future distribution of mangroves but that the effect will vary dramatically depending on the local rate of sea-level rise and the availability of sediment to support re-establishment of the mangroves. The predicted rise in mean air temperature will probably be of little consequence to the development of mangroves in general but it may mean that the presence of mangroves will move further north and south, though this will depend on a number of additional factors. The effect of enhanced atmospheric CO_2 on the growth of mangroves is unknown at this time but that there is some evidence that not all species of mangroves will respond similarly. The socio-economic impacts of the effects of climate change on mangrove ecosystems may include increased risk of flooding, increased erosion of coast lines, saline intrusion and increased storm surges.

Introduction

Mangrove forests are characteristic littoral plant formations of tropical and sub-tropical sheltered coast lines. The plant species that are known as mangroves are derived from a variety of families and they vary in their dependence on littoral habitat. The total worldwide mangrove area is estimated at not less than 170 000 km^2 and there are considered to be some sixty species of trees and shrubs that are exclusive to the mangrove habitat. Mangroves support genetically diverse communities of terrestrial and aquatic fauna and flora that are of direct and indirect environmental, economic and social value to human societies throughout the world. Mangrove ecosystems are being subject to increasing non-sustainable development as economic and population pressures rise in many of the coastal areas of the tropical parts of the world. Mangrove forests are an important source of fuelwood in developing countries and energy for detritus based coastal food-chains, involving fish, molluscs and crustacea of economic value. Mangrove forests also help reduce coastal erosion in some regions of the world by dissipating the force of wave action.

Mangrove ecosystems may be considered dynamic and there is geological and contemporary evidence that they can extend or contract rapidly in response to regional topographical and climatic changes. Such ecosystems are also likely to be affected by stresses related to activities by man and they will exhibit marked spatial and temporal fluctuations as a result of such influences. The problem is to identify changes to mangrove ecosystems due to climate change induced by man's activities from changes that occur naturally. The primary climatic factors to be considered are temperature, atmospheric carbon dioxide concentration and sea level rise.

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 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 our 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 an ice age. 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 greenhouse gases are carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons (CFCs). The commencement of the industrial revolution lead to great amounts of fossil fuel being consumed 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 1 summarises how the concentrations of these gases are being affected by human activities.

It has been estimated that global average warming has been 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 conditions 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 atmospheric carbon dioxide concentration in 1990 was 353 ppmv, which is about 25% greater than the pre-industrial (1750–1800) value of about 280 ppmv, 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.

A factor important to mangrove ecosystems is the extent of sea level rise that might accompany an increase in mean global temperature. It is not easy to estimate sea level rise but the estimate is that the average rate of rise in sea level over the last 100 years has been 1.0–2.0 mm y^{-1}. In general the rise appears to be due to thermal expansion of the oceans and to increased melting of mountain glaciers and the margin of the Greenland ice sheet. The worst case scenario discussed above estimates that by the year 2030 global mean sea level will be 8–29 cm higher than today with a best estimate of 18 cm. By the year 2070, the rise in will be 21–71 cm, with a best estimate of 44 cm.

A factor that may be important for the future of mangrove ecosystems is any change in precipitation. It is estimated that there will be a substantially wetter atmosphere as the mean global temperature increases. However, in the tropics though the mean zonal value of precipitation may increase throughout the year there may be also areas of decrease. An accompanying phenomenon is the area of occurrence, frequency and intensity of tropical storms. There is some slight evidence that all of these may increase but it is by no means conclusive.

Table 1. Global man-induced environmental 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)		+6.0cm/decade (uncertainty: 3–10 cm/decade)	+60.0 cm

Response of mangrove ecosystems

Sea-level rise

It is difficult to generalise about the effect of climate change on mangrove ecosystems as each system is very much the product of local topographical, climatic and anthropological influences. However, as all mangrove systems occur somewhere between high and low tide marks it is clear that they are likely to be significantly influenced by any changes in sea-level. Different mangrove species appear to have a marked preference for the level of salinity of the surrounding environment and therefore they are to be found at varying distances and elevations from the seaward edge reflecting the degree of mixing of the freshwater input and tidal influx.

Mangrove ecosystems accumulate peat or mud and this gives them the opportunity to adjust to a rising sea level. If the sediment accretion rate equals the rate of rise of sea-level then inundation preferences of the different mangroves species can be maintained. If the rate of sea-level rise exceeds the rate of accretion then some rearrangement of existing vegetation will take place and loss of mangroves will occur if the mean tide level becomes higher than the elevation of the substrate. Ellison & Stoddart (1991) conclude that in the case of low limestone islands where there is little significant allochthonous sediment input, mangrove ecosystems should be able to keep pace with a rising sea-level of 8–9 cm per 100 years, are under stress at between 9 and 12 cm per 100 years and cannot adjust at rates above this level. They believe that the predicted rates of sea-level rise caused by man induced climate change will be too fast for such mangroves to adjust and that there will be a collapse of the mangroves as a viable coastal ecosystem on low islands. The situation with high islands and continental shores will be more dependent on the amount of allochthonous sediment available and that can be highly variable (Woodroffe & Grindrod, 1991). In the case of some macrotidal estuaries, tidal influences can override riverine influences and vertical accretion within the mangrove ecosystem becomes chiefly due to tidally-driven reworking and transport of marine sediments. In northern Australia great mangrove swamps emerged following a dramatic rise in sea-level during the period 8000–6000 BP. It appears from the geological record that previous sea-level fluctuations presented a series of crises and opportunities for mangroves and that they tended to survive or even expand in several refuges, the most likely being continental coastlines with healthy sediment budgets. Woodruff & Grindrod (1991) comment that the factors influencing mangrove establishment at latitudinal limits are complex and incompletely known but that it is likely that previous dramatic temperature perturbations have had less impact than changing sea-levels on mangrove distributions especially on remote oceanic islands.

Temperature rise

Mangrove species show considerable variation in their sensitivity to temperature but the majority of them seem to produce maximal shoot growth when the mean air temperature rises to 25 °C and only *Avicennia marina* continues to produce leaves when the mean air temperature drops below 15 °C (Saenger & Hutchings 1987). It would appear therefore that if the average air temperature increases that the species composition of the mangrove forests may change and the presence of mangroves move further north and south. There is little evidence as to the effect of extremely high temperatures on mangroves but Saenger and Moverly (1985) show that some species demonstrate a declining leaf formation rate at temperatures above 25 °C. The optimum leaf temperatures for photosynthesis in mangroves appears to be 28–32 °C and photosynthetic capacity falls to close to zero at leaf temperatures of 38–40 °C (Clough *et al.*, 1982; Andrews *et al.*, 1984). It is generally accepted that plant development will be accelerated by increased temperature, as long as the temperature reached does not exceed an upper threshold. Very little is known about the effect of changing temperature on metabolic processes in mangroves. Superficially the predicted global warming of between 1.5 °C and 4.5 °C over the next century would seem likely to be of little consequence for the development of various species of mangrove. This impression is reenforced when the expected increase is compared to the diurnal oscillations in temperature, which can be in excess of 20 °C at the limits of mangrove occurrence. However, the temperature increases could become significant when the cumulative effects of temperature on plant development are considered. The elevation of the average temperature of the plant will be a critical factor in terms of growth but how this will be manifest in mangroves remains unknown. Soil warming that will accompany any global temperature rise could escalate the increase of atmospheric CO_2 through stimulation of soil respiration. This is one of several positive feedback mechanisms that may affect global climate.

Rise in atmospheric CO_2 levels

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). There is some evidence that elevated CO_2 stimulates plant growth at least in agricultural plant species (Kimball, 1983; Cure & Acock, 1986) where most of the experiments have been carried out with green house grown plants. Eames & 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 sedge 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 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 in response to elevated atmospheric CO_2 levels.

In the case of mangroves, Ball & Farquahar (1984a, b) reported that for *Aegiceras corniculatum* and *Avicennia marina* the rate of photosynthesis was limited by stomatal conductance to CO_2 and the internal efficiency of carboxylation involving the enzyme Ru Bp carboxylase. These results suggest that for these mangroves photosynthesis would be enhanced if the ambient CO_2 levels were increased. Contrary to these results, Cheeseman *et al.* (1991) working with *Bruguiera parviflora*, *Bruguiera gymnorrhiza* and *Rhizophora apiculata* suggested that the photosynthetic performance was unlikely to be enhanced by increased levels of ambient CO_2. The effect of CO_2 enrichment on mangrove forests cannot be interpreted within a simple framework as it will depend on complex interactions between several different physiological and environmental factors. Information is needed from long term assessments of growth where high CO_2 concentration, temperature, water stress and nutrient stress are controlled.

Water availability

It is well established that mangroves flourish in warm wet humid conditions where there is plentiful input of fresh water into their normal saline environment. One of the effects of global warming may be to change the pattern of precipitation in the tropics and this could have a profound effect on the growth of mangrove areas. The growth rate of mangroves is critically related to the availability of water to the trees and this is reflected in the soil water content and soil salinity. As most mangroves are tidally inundated, soil water content only becomes a problem when the inundation is occasional and the rainfall very limited. Soil salinity, however, characterises the mangrove habitat and growth of some mangroves has been shown to be maximal under relatively low salinities (Burchett *et al.*, 1984; Clough, 1984). As the salinity of the soil increases the mangroves face the problems of increasing salt levels in the tissues and decreasing availability of water. The increasing salt levels in the tissue may bring about a lessening in the net assimilation rate per unit leaf area (Ball 1988) and therefore reduce growth.

Water availability can also control growth and growth can be expressed as the product of the transpiration rate and the carbon gain per unit water loss (or water use efficiency). As the salinity increases above optimum levels the stomatal conductance declines with an accompanying decrease in transpiration rate, probably reflecting the decline in water potential of the soil. The reduction in stomatal conductance inhibits CO_2 diffusion into the leaf and leads to low assimilation rates. The humidity of the surrounding atmosphere and leaf temperature are also critical factors in these processes.

Mangroves have unusually high water use efficiencies (Ball, 1988) showing adaptation for minimal water use for a given carbon gain, which is reflected in relatively low rates of growth. Clough & Sim (1989) suggest that the water use efficiency of mangroves increases with increasing environmental stress thereby maximising photosynthetic carbon fixation while minimising water loss. Ball & Munns (1992) state that elevated CO_2 can enhance the water use efficiency of mangroves but that this may or may not result in enhanced growth. They also suggest that there may be enhanced growth with elevated CO_2 if growth is limited by water, carbon and nitrogen, but that elevated CO_2 would have little effect on growth when the salinity is too high for a species to maintain water uptake.

If the change in precipitation patterns in mangrove areas is such as to reduce soil salinity then an improvement in growth rates can be expected in some species.

Socio-economic impacts

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 value 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. 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; Padma Narsey 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 main consequences will be:

- increased risk of flooding of low lying areas
- increased erosion of vulnerable soft coast
- increased risk of saline intrusion
- possible increase in frequency of storm surges

The loss of economic resources which might occur as a result of sea level rise is extremely difficult to model or predict and will depend heavily on local factors. It must be appreciated that the changes taking place in coastal areas either due to natural causes or human activities are probably already greater than any that might be expected from the predicted change in global climate.

Future action

In 1991 a meeting of experts (UNEP-IOC-WMP-IUCN/GCNSMS-11/3 report no 69) recommended that long-term global monitoring systems be established for coral reefs and mangroves to measure the effects of climate change. In 1992 a UNEP-UNESCO task team was established to consider the impact of climate change on mangroves. The task team has recommended that a long term monitoring and study programme should be implemented at a small number of primary sites for long term and well designed experiments. Additional secondary sites should be selected for the gathering of complementary information and intermittent or routine studies covering a wide geographical distribution of sites and types. The primary sites should be well documented and include examples of a deltaic system, an arid coast and a low island. It was felt that these distinct habitats would provide information that would indicate any effects that might begin to occur as a result of climate change.

Such studies would have to be on a long term continuous basis if any trends are to be identified. Every effort would have to be made to minimise the effects of human activity and episodic natural events by selecting relatively stable sites.

Acknowledgments

I should like to acknowledge discussions with members of the UNEP-UNESCO Task Team on the Effect of Climate Change on Mangrove Ecosystems that have contributed significantly to the development of this paper.

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