Mangrove Forests, Climate Change and Sea Level Rise:

Hydrological Influences on Community Structure and Survival, with examples from the Indo-West Pacific

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1. Introduction

Mangroves represent the dominant soft bottom plant communities of the marine-terrestrial transition in tropical and subtropical regions. As a consequence of the range of spatial and temporal variation in physical factors found in such environments the biological communities display remarkable adaptations which permit them to survive under such harsh environmental conditions. The plant species are members of terrestrial families which have adaptations to survive under conditions of high salinity, low oxygen and nutrient availability in the soil, wind and wave action, and substrate instability. The animals are, like the plants, representatives of largely terrestrial groups. In contrast the aquatic animal community is dominated by members of essentially marine families which are adapted to variable salinity, turbid conditions and to feeding directly or indirectly on materials from the dominant primary producers.

The majority of the world's mangrove forests are distributed along the tropical and sub-tropical shorelines of developing countries where they are extremely important to coastal societies for both subsistence and commercial purposes. The figures for area of mangroves in Figure 1 are based on the review by Hutchings and Saengar (1987) and are probably an over-estimate of current mangrove cover. Mangrove ecosystems provide:

- supplies of natural renewable resources such as fuelwood (including charcoal), tannin, dyes, poisons, alcohol (from Nypa sap), construction materials (timber and thatching), and food (both plant and animal);

- nursery areas for offshore, commercial species of fish and prawns;

- coastal protection from tidal erosion and storm surges;

- sediment traps for land accretion;

In addition they serve as habitats and refugia for a large number of species of conservation concern. Mangrove habitats have in the past been viewed as economically unproductive areas and as a consequence have been felled to provide timber and fuelwood and areas for mariculture and agriculture which often prove unsustainable. As a consequence of growing coastal populations mangrove habitats are being destroyed and degraded at an alarming rate. Degradation of mangrove habitats renders them increasingly susceptible to the potentially adverse effects of climatic change and sea level rise and reduces their capacity to provide environmental goods and services on a sustainable basis. Loss of fringing mangroves exposes the shoreline to potential increases in erosion, which may be further increased under scenarios of global climate change and sea level rise.

This overview provides an evaluation of the potential responses of mangroves as a community, to changes in key environmental variables including changes to the hydrological regimes of coastal and estuarine areas. Data concerning past distribution, present global distribution

patterns and ecological data on community structure and species diversity are used to provide insights into the possible responses of mangroves to climate change and sea level rise. This approach involves an examination of key environmental factors affecting the distribution and abundance of mangrove plants and associated fauna, and attempts to evaluate how key variables may change in a warmer "Greenhouse" world. Some aspects of the potential impacts on mangrove fauna and human societies which use and depend on mangroves for subsistence, and commercial purposes are discussed, with emphasis on the island of New Guinea.

2. Present Mangrove Distribution and Diversity

2.1 Global distribution of mangroves

Figure 1 displays the present extent, geographic range and diversity of mangrove communities world-wide. The centre of generic diversity amongst the dominant plants is the island of New Guinea and the north and east coasts of Australia within the tropical belt. Frodin (1985) suggests that the mangrove flora of the Indo-west Pacific is composed of some 40 species of obligate, erect, woody dicotyledons which together with five to six other obligates such as *Nypa*, *Acrosticum* and *Acanthus* form the "core" species of the mangrove community. In addition the flora includes a large and undefined number of facultative species including other trees, herbs, epiphytes, lichens, algae, and fungi. There is an extensive body of literature on the mangrove habitats of the Caribbean region and comparatively less on the more diverse mangroves of other regions. Diversity is low in the Caribbean area with only four genera and seven species of mangrove trees in contrast to the thirteen genera and thirty seven species found in present day New Guinea mangrove communities.

The thirty seven species of New Guinea obligate mangrove trees include representatives of all genera currently found in Australia and south east Asia with the sole exception of the south-east Asian mangrove genus *Kandelia*. Frodin (1985) suggests that the mangrove communities of the western Pacific can be divided into four major biogeographic systems based on diversity and floral composition:

- "Bay of Bengal" with low species diversity;
- "South China Sea" which includes the greater Sunda islands, west Sumatra and southern Java having between twenty seven and twenty nine core species;
- "South Central Malesia" including the Philippines and Sulawesi through to southern New Guinea and Australia, again with between twenty seven and twenty nine core species; and,
- "East Malesia" including northern New Guinea, the Bismarck archipelago and Milne Bay Islands, with between twenty four and twenty six core species in any one location".

On the western side of the Indian ocean mangrove communities are much less diverse with only seven genera of trees in East Africa and four in the drier Arabian region. Moving across the Pacific to the Pacific coast of central and Latin America one finds the Atlantico-east Pacific mangrove flora which is similar in species and generic composition to that of the Caribbean. Some four genera and seven core species occur along this coast suggesting the establishment of mangrove communities in this area prior to the closure of the Isthmus of Panama. The

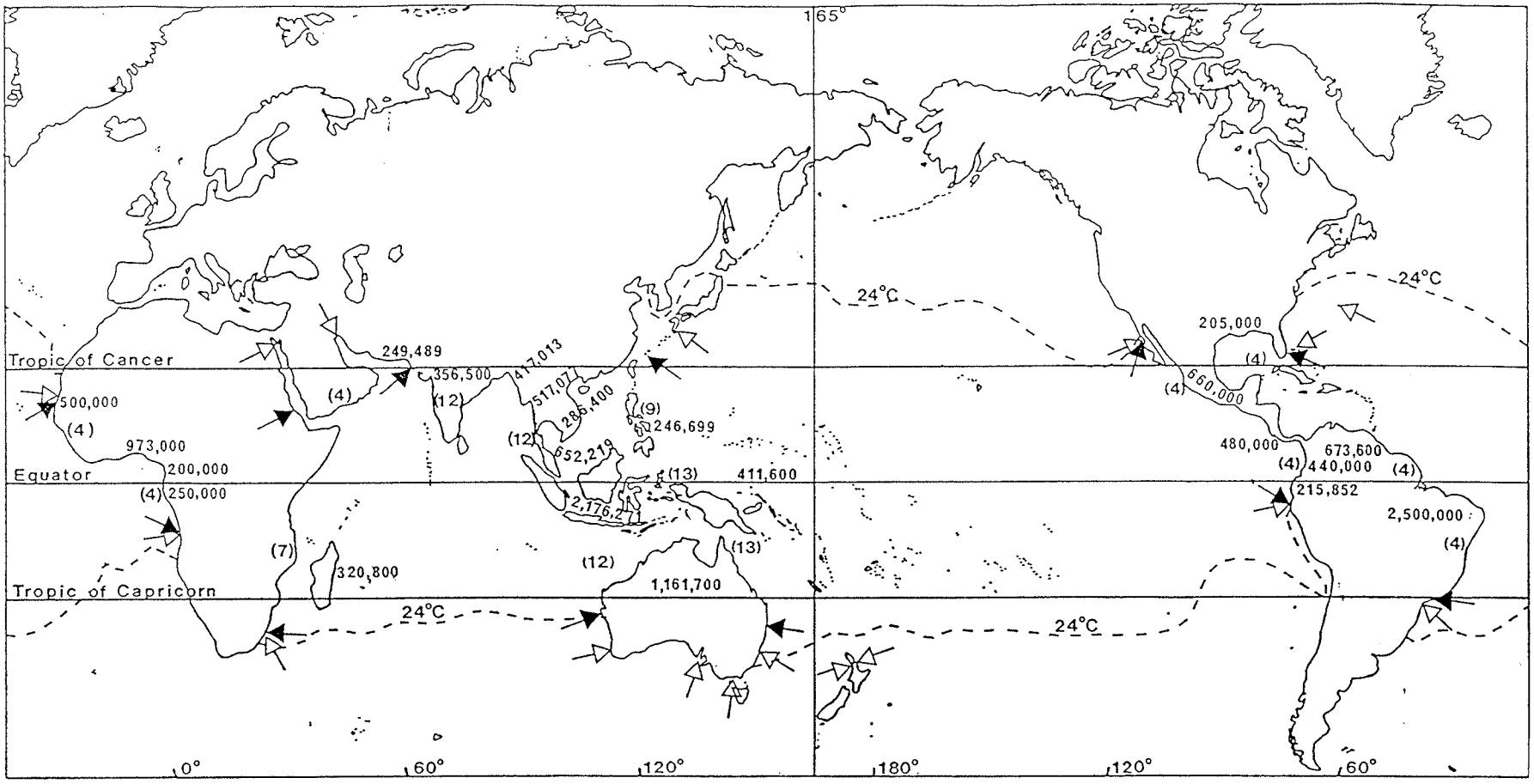


Figure 1. Global distribution of mangroves in relation to water temperature

(24° isotherm, mean monthly temperature of warmest month; numbers indicate the extent of mangroves by country in hectares; numbers in parentheses are the number of mangrove genera; solid arrows indicate the limits of *Rhizophora* distribution; and, open arrows other genera such as *Avicennia*; the open arrow in the Atlantic indicates the occurrence of mangroves in Bermuda. Data derived from various sources).

mangroves of the Atlantic coasts of Africa and South America support a similar range of species to the Caribbean region thus constituting a single Atlantic mangrove province.

2.2. The fossil history of mangroves

The fossil history of the genera of mangrove trees is reviewed by Hutchings and Saenger (1987) from which it is evident that many genera had much wider distributions in the recent past than they have today. Hypocotyls of *Ceriops* and *Paleobruguiera* are recorded from London clay deposited during the Eocene, whilst *Nypa* pollen is recorded from Europe, South America and southeast Asia by the end of that geological period. On the basis of the rather scanty fossil, evidence together with the present day diversity, Specht (1981) concluded that the centre of origin of mangrove communities was more likely to be the area of Australia and New Guinea (Sahul) rather than, as previously postulated, the Malayan region (Sunda). Following Specht (1981), Hutchings and Saenger (1987) suggest that mangrove communities evolved during the Cretaceous around the fringes of the Australian and New Guinean landmasses, spreading through southeast Asia and the Indian region into the Atlantic through the Mediterranean basin. As noted above the mangroves of the western coasts of central and south America were probably established from the Caribbean prior to the closure of the isthmus of Panama.

Palaeobotanical evidence from Australia indicates that genera such as *Nypa* and *Sonneratia* had more southerly distributions along the Australian coast during the Eocene (Churchill, 1973; Hutchings and Saenger, 1987). Examination of core samples from Enewetak atoll in Micronesia shows the presence of an intertidal mangrove swamp during the Miocene (Leopold 1969) at a time when the island included areas of limestone above sea level. Mangroves are currently absent from this and nearly all other atoll islands of Micronesia. Ellison (in press) in reviewing data for low islands in the Pacific and Caribbean, concludes that during the early Holocene when rates of sea level rise were rapid extensive mangrove systems did not exist and that such communities were only established during the mid-Holocene stabilization of sea levels.

2.3 Mangroves and temperature

To understand the patterns of past and present mangrove distributions and the possible changes which might occur in a warmer world, the physical factors which affect the establishment and survival of these communities must be examined. Figure 1 shows a close correlation between the present distribution of mangroves and the 24°C sea surface isotherm for the warmest month. The limits of *Rhizophora* are also indicated and it can be seen that this element of the community is not found at the extremes of the latitudinal ranges. In these locations mangroves are frequently present only as single species stands representing relicts of a once more diverse community. The sole mangrove species in New Zealand is *Avicennia marina* whilst along the south coast of Australia isolated stands of the same species occur in locations where the air temperature drops as low as 4°C (MacNae, 1966). MacNae (1963) states that in southern Africa *Avicennia marina*, the most southerly distributed species, occurs only in areas where the mean air temperature does not fall below 13°C. Species diversity within the mangrove community follows the characteristic cline from high diversity in tropical latitudes to low diversity at their geographic limits at the sub-tropical, warm-temperate boundary (Hutchings & Saengar, 1987).

Whilst the empirical correlation with water temperature is obvious from the data, the causal mechanisms are far from clear. Chapman (1977) noted the correlation between mangrove distribution and the 16°C isotherm for air temperature of the coldest month. Walsh (1974) and Chapman (1975; 1977) suggested that extensive mangrove development was only possible in areas where the average air temperature of the coldest month exceeds 20°C and where the seasonal range does not exceed 10°C. Despite the general applicability of these observations exceptions do occur as noted above. Specht (1981a) recognised three groups of Australian plants on the basis of distribution and temperature regulation of shoot growth:

- A tropical sub-tropical group including species in which shoot growth was initiated only above 25°C;

- A warm temperate group showing shoot growth between 15 and 25°C; and,

- A cool-temperate group showing shoot growth when temperatures are above 10°C.

Few data are available for temperature limitations to shoot growth for most areas of mangroves, but Saenger and Moverley (1985) examined leaf growth in nine species. On the basis of these and other data Hutchings and Saenger (1987) conclude that most of the fourteen Australian species for which data are available can be classified as warm temperate with leaf production ceasing below around 15°C and peak production occurring between 21 and 27°C. *Avicennia marina*, classed by them as a cool-temperate species, commences leaf production above 12°C and maximal production occurs around 20°C. This species was thought to be common in New Guinea where air temperatures rarely falls below 20°C, suggesting that substantial differences in the physiological responses to temperature between latitudinally separated populations of widespread species may confound this classification. True *A. marina* may not occur in New Guinea however and Frodin & Leach (1982) suggest that New Guinea populations represent the species *A. eucalyptifolia* . The only Australian species classified by Hutchings and Saenger (1987) as being tropical-subtropical is *Xylocarpus granatum* in which leaf production ceases below 26°C and peaks at temperatures in excess of 28°C.

Another line of evidence concerning the upper thermal tolerance of mangroves is derived from studies in thermally polluted areas in the Caribbean. Canoy (1975) showed that in Puerto Rico *Rhizophora mangle* developed more stilt roots per unit area when subjected to an increase in temperature of 5°C. He further showed, as did Lugo and Snedaker (1974), that under temperature-stressed conditions this species produced more, but significantly smaller, leaves. Seedlings of *Avicennia germinans* died when subjected to increased temperatures in areas where established and mature trees were apparently unaffected (McMillan, 1971). In a study of seedling survival under temperature stress Banus (1983) showed that survival of *Rhizophora mangle* was zero after four months in a thermally polluted site where water temperatures were between 36.1°C (mean daily minimum) and 38.1°C (mean daily maximum). At another thermally polluted site, where temperatures were lower: mean daily minimum 34.2°C; mean daily maximum 37.6°C; but still higher than unpolluted areas (29°C) survival was 75%.

Temperature affects photosynthetic activity, water loss and stomatal opening, transpiration and salt loss. Consequently since mangroves occur in a high salinity environment in tropical regions

they show xeromorphic adaptations. A variety of studies have shown that for most mangrove species photosynthesis declines sharply above 35°C with little or none occurring above 40°C. (Moore *et al.*, 1972, 1973; Clough *et al.*, 1982). The effect of solar insolation on *Avicennia marina* (Attiwill & Clough, 1980) suggests that this species is saturated above 350 W m^{-2}. These authors also demonstrated that leaves growing in direct sunlight (sun leaves) have a rate of photosynthesis approximately 4.5 times that of leaves growing in the shade (shade leaves). These two types of leaves are formed by several Indo-Pacific species and differ morphologically, with the sun leaves being generally more xeromorphic than the shade leaves (Saenger, 1982). Similar differences have been demonstrated in the case of sun and shade leaves of Caribbean *Rhizophora mangle* and *Avicennia germinans*. Sun leaves have twice the photosynthetic rate of the shade leaves whilst at night the shade leaves had respiratory rates which were four times as great as those of the sun leaves (Lugo *et al.*, 1975).

Whilst solar insolation and low temperatures may play a part in limiting the present distribution of mangroves at higher latitudes it would appear that neither of these factors significantly limit the distribution of mangroves within the tropical and subtropical zones. In a warmer world, incident solar radiation may change as a consequence of higher cloud cover. This in turn may alter the balance between sun and shade leaves thus affecting overall growth and productivity of mangrove species. The extent to which increased temperatures in tropical regions combined with changes to other ecophysiological conditions may affect mangrove growth and productivity cannot be adequately assessed at this time.

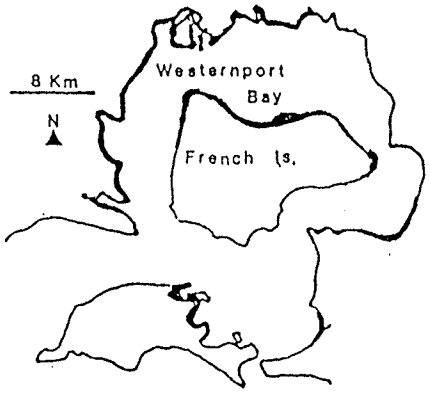
2.4 Mangroves, coastal geomorphology and island type

Thom (1982) recognised five categories of terrigenous sedimentary coast on which mangroves are generally found (Figure 2) and this classification with the addition of a sixth class is widely accepted in the western Pacific (Hutchings and Saenger, 1987). The categories are:

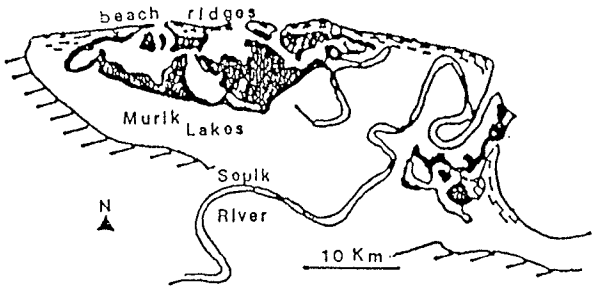
- alluvial plains, dominated by freshwater and sediment inputs;
- tidal plains in which the influence of the tides is greater than in the case of alluvial plains;
- barriers and lagoons where offshore shoals develop;
- composite alluvial plains and barriers where wave energy is high;
- drowned bedrock coasts;
- coral coasts where mangrove growth is based on carbonate sediments, autochthonous peats or consolidated substrates.

On a global scale this last class is relatively unimportant, however it is a widespread category in the Pacific Basin, although the mangrove communities in such environments rarely develop the complex zonation displayed in other coastal types. The most extensive stands of mangrove tend to develop in alluvial and tidal plains, although coastal barrier and lagoon systems may

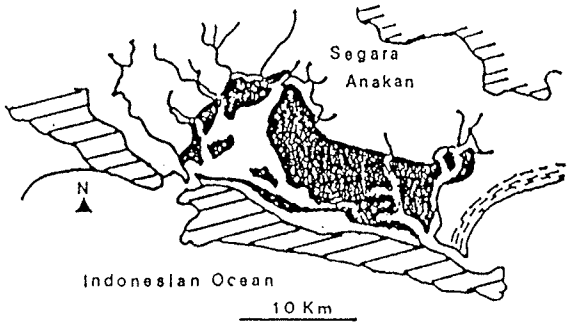
Figure 2. The major geomorphic classes of mangrove coastline (various sources)



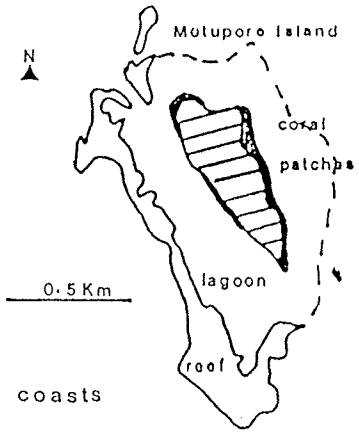
Drowned bedrock coast



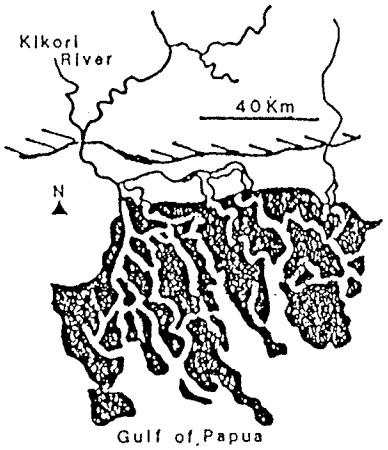
Composite alluvial plains and barriers



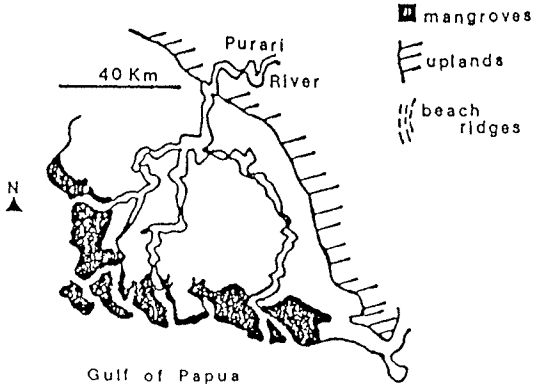
Barriers and lagoons



Coral coasts



Tidal plains



Alluvial plains

support complex mangrove communities in areas with minimal human interference. Within the Indo-west Pacific the greatest extent of mangrove stands are seen in Melanesia, on prograding shorelines.

The diversity of mangrove communities within the Pacific Basin demonstrates two obvious features, which are also found in coral reef communities:

1) species diversity declines as one moves north or south away from the equatorial Pacific;

2) species diversity declines from west to east across the Pacific;

Classical island biogeographic theory would suggest that these patterns may be explained in terms of land area and distance between island groups. This is illustrated in Table 1. From these data one might conclude that Sub-Province XIII, being closer to the New Guinea land mass has more islands with mangroves simply as a result of distance effects. The northern Mariannas are further away and at a lower latitude, while the Marshall islands are also further away but within the same latitudinal zone as the Federated States of Micronesia. Similarly the proportion of large Islands having mangrove stands (six out of thirteen) is greater than the proportion of small islands with mangroves (twelve out of ninety).

Table 1. Numbers of islands in three different Pacific sub-provinces having or lacking stands of mangroves. (Based on data contained in Dahl, 1986).

Island size	< 20 km^2		> 20 km^2	
Mangroves:	Present	Absent	Present	Absent
SUB-PROVINCE				
XII northern Mariannas	0	7	1	6
XIII Federated States of Micronesia	8	41	5	1
XIV Marshall Islands	4	30	0	0
TOTALS	12	78	6	7

A closer examination of these data however, suggests that other factors are important. If these data are re-arranged in relation to island type (Table 2) then it can be clearly seen that raised limestone islands (coral islands) and atolls do not differ significantly in terms of the occurrence of mangrove stands, and that within the volcanic class of islands the occurrence of mangroves is not related to island size. Equally clearly however it can be seen that the occurrence of mangroves on volcanic islands (ten out of eleven) is significantly more frequent than on islands of the other two types (three out of forty three). In general volcanic islands have a greater altitudinal range than the other two types hence orographic rainfall and runoff also tend to be higher as does the flux of terrigenous sediments to near-shore waters. Both runoff and allochthonous sediment inputs may therefore be important to the establishment of mangrove ecosystems on islands.

Table 2. Numbers of islands of different types in the Federated States of Micronesia with and without stands of mangroves. (Data based on Dahl, 1986)

Island size	< 20 km^2		> 20 km^2	
Mangroves:	Present	Absent	Present	Absent
ISLAND TYPE				
Atoll	2	26	0	0
Coral, raised limestone	1	14	0	1
Volcanic	5	1	5	0

In Melanesia high runoff rates and sediment inputs into the coastal systems result in accreting shorelines associated with sheltered bays and deltaic floodplains. In contrast the absence of all mangroves from most atolls in the central Pacific may be explained by the absence ofsurface fresh water and hence significant runoff and the absence of terrigenous sediment inputs to the coastal environment. Similarly, the decline in species diversity from west to east across the Pacific may reflect the smaller land masses and hence smaller areas suitable for mangrove stands in the islands of the central and eastern Pacific rather than an inability to disperse to these archipelagos. The smaller land masses and lower altitudes result in lower rainfall and hence comparatively lower run-off and sedimentation. The presence of mangroves from Enewetak at a time in the Miocene when this was a raised island suggests that mangroves had the dispersal ability to reach this location. Their absence at the present time from the flora of this and most other nearby atoll systems suggests that atoll soils and tidal environments are generally unsuitable for their establishment and maintenance. Ellison (in press) argues that present rates of sea level rise are responsible for loss of mangrove systems in many small island environments. In most cases where mangroves occur on coral or atoll islands peculiarities of the island geomorphology result in mangroves being established around inner lagoons or inland ponds (Dahl, 1986).

2.5 Mangroves and sediment

Those factors which have been perceived in the past as playing an important role in limiting the distribution of mangrove communities and species include:

- salinity, itself a function of: substrate elevation; freshwater inputs to the system; tidal range; and coastal geomorphology;
- substrate type;
- coastal water movements and dispersal ability; and,
- terrigenous sediment inputs.

Figure 3 shows the distribution of mangrove forests around the island of New Guinea and on its satellite islands. All major areas of mangrove development are associated with sources of terrigenous sediment, relatively high freshwater inputs and protected or rapidly prograding shore-lines. The rivers and catchments of Papua New Guinea are indicated in Figure 4 to give a measure of the freshwater inputs into the coastal ecosystems, while Figure 5 shows the extent of mangroves fringing the Gulf of Papua on the South coast of Papua New Guinea.

The presence of mangroves in accreting coastal areas led to the mistaken belief that mangroves were responsible for causing sedimentation and hence creating land. As Percival and Womersley (1975) pointed out mangroves do not create accreting shorelines. Once established in such situations, they may hasten the rate of sediment deposition through reducing the scouring action of waves and by forming sediment traps with their complex, inter twined root systems. Bird and Rosengren (1985) have shown that in Australia (Westernport and Cairns Bay), *Avicennia marina* growing on a muddy substrate acted as a sediment trap where wave action was weak and fine-grained sediment available. The result was progression of the shore line and build up of a depositional terrace in the upper inter-tidal. Where the mangroves died back, wave action resulted in scouring and erosion which ceased in areas of mangrove regeneration (Figure 6). In the Purari Delta of the Gulf Province, Papua New Guinea, changes in the volume of water and hence sediment flowing through the various distributary arms result in patterns of local erosion of mature mangrove stands in some areas and active prograding shorelines and younger pioneer mangrove communities in others.

Along shorelines receiving high allochthonous sediment inputs the extent of mangroves is usually much greater than along stable shorelines where the mangroves may be restricted to a relatively narrow strip. Along stable shorelines the loss of sediments to offshore sinks equals the rate of sediment input to the mangrove system and contrasts with areas such as the Purari Delta where the rate of sediment input exceeds the rate of offshore loss; the shore-line is accreting and the mangroves form a belt some 30-60 kilometres wide.

The seaward extension of mangroves is limited by inundation, since no mangrove can survive continual or repeated inundation of its crown. The landward extent of mangroves appears to be limited indirectly by saline influences; outside the zones of saltwater penetration the terrestrial halophobic plants are more successful than the mangroves. Adaptations of mangroves for survival under the high saline conditions of the inter-tidal ensure their survival in such situations. Mangroves species such as *Excoecaria agallocha* are quite capable of growing and surviving in freshwater environments, their rare occurrence in such situations in nature suggests that their landward distribution is limited by competition and that such communities are occupying (in spatial terms) a realised niche which is smaller than their fundamental niche.

In addition to allochthonous sediment inputs mangroves produce litter which under conditions of low tidal flushing serves to elevate the substratum. Peat build-up in mangrove communities may be an important mechanism for extension of the mangrove ecosystem seaward under conditions of low sediment input but under conditions of high tidal flushing much of the litter may be removed and the rate of vertical accretion of mangrove habitats considerably reduced.

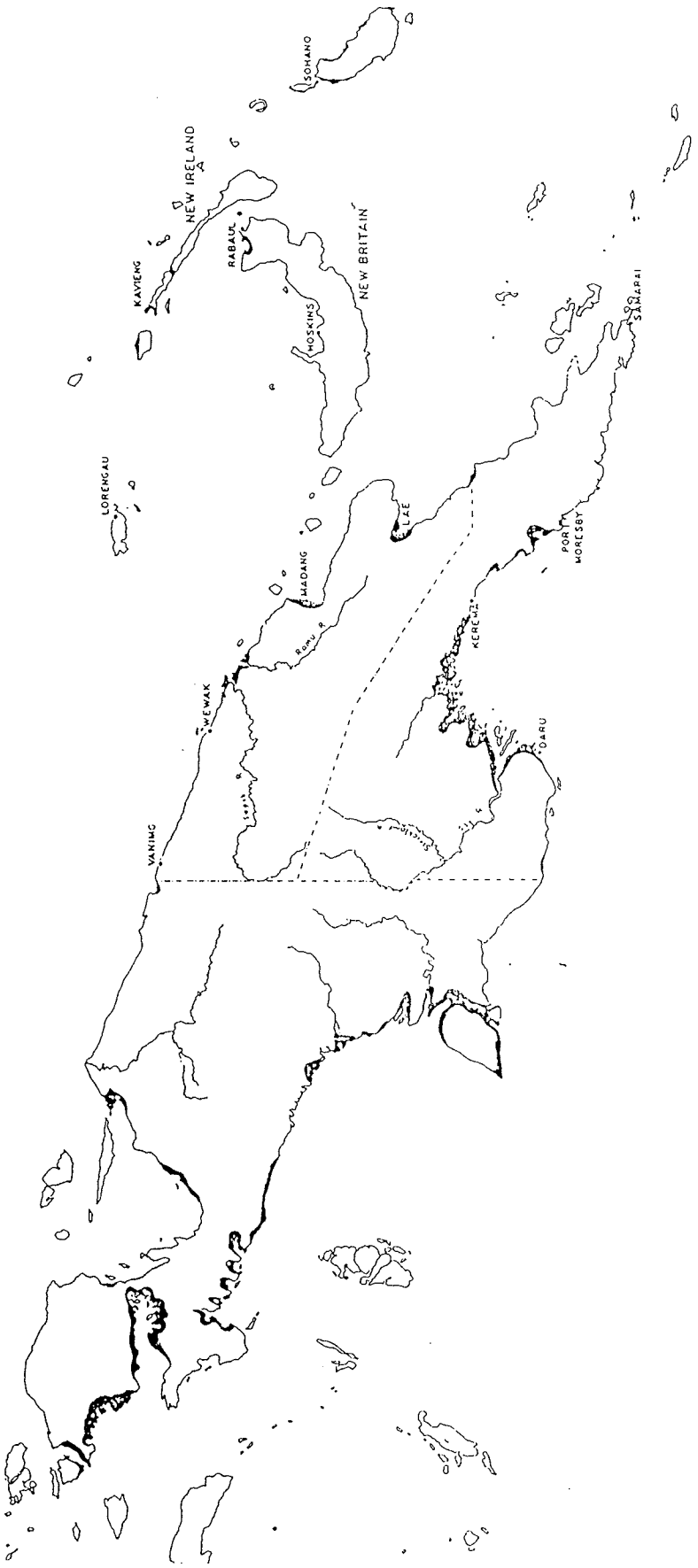


Figure 3. The distribution of mangroves around the coastline of New Guinea (from Percival and Womersley, 1975)

Figure 4. Major river catchments of Papua New Guinea

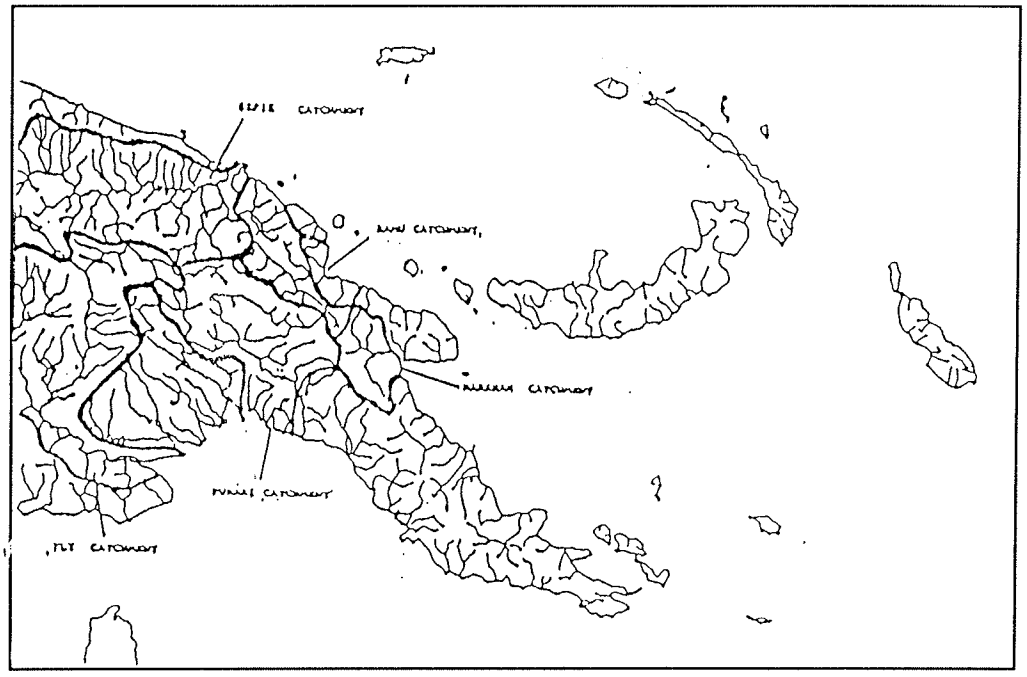


Figure 5. The mangroves of the Gulf of Papua, Papua New Guinea (after Thom & Wright, 1983) (Solid arrows indicate the direction of sediment movements).

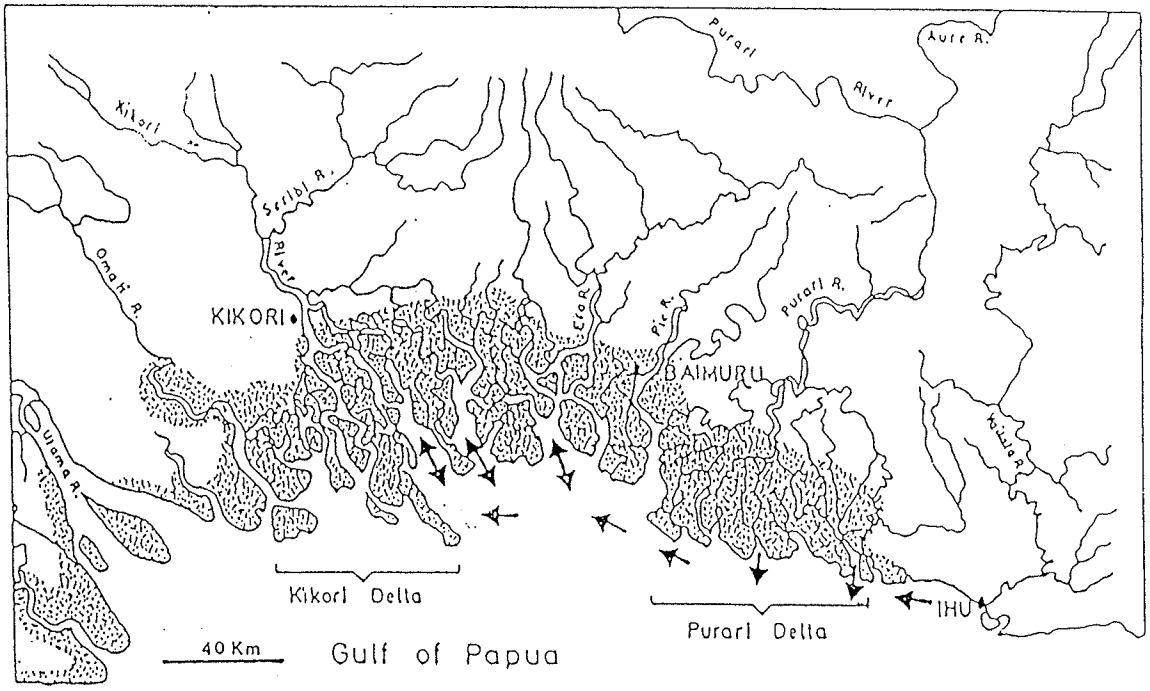
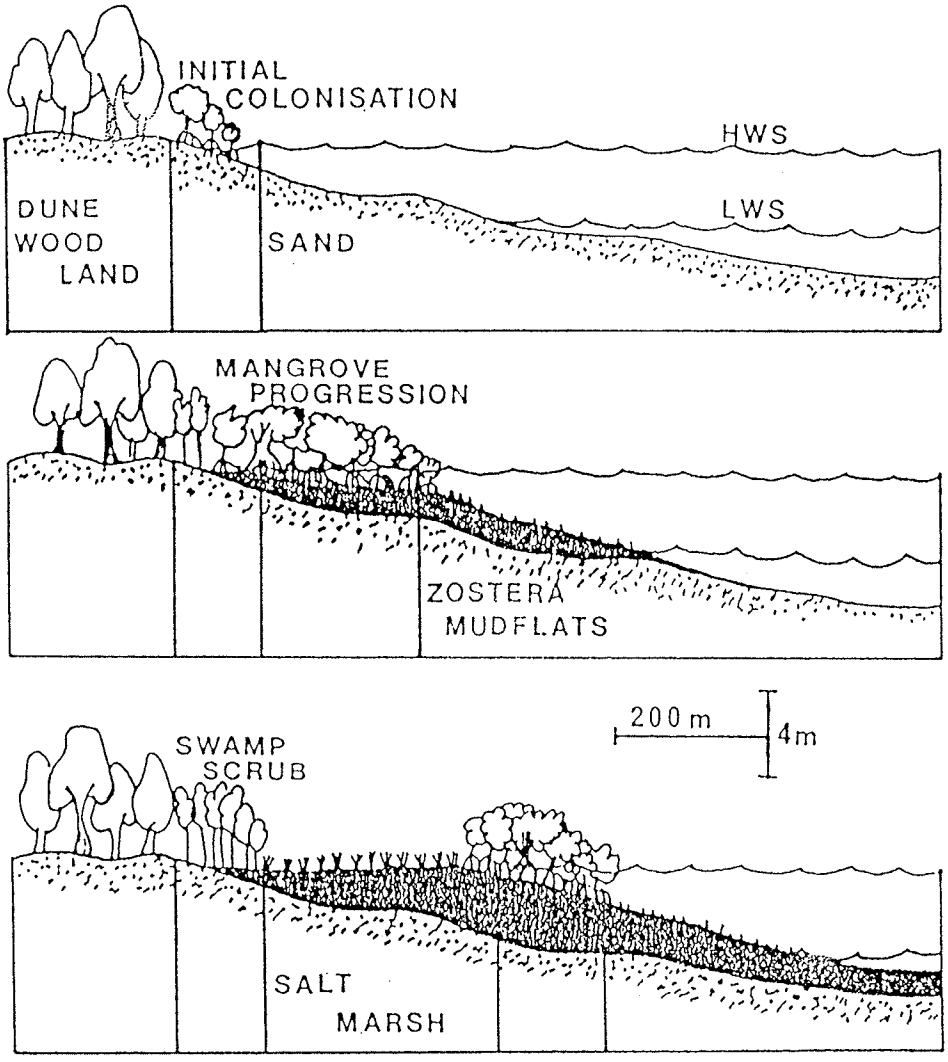


Figure 6. Shoreline progression following mangrove colonisation, Westernport Bay, Australia (from Bird & Rosengren, 1985)



2.6 Mangrove succession and zonation

Mangrove zonation has been interpreted as succession, however as Johnstone (1983) has pointed out there is no true mangrove climax, as continual progression of the shoreline ultimately leads to the establishment of a terrestrial vegetation climax. As Percival and Womersley (1975) note, mangrove species on the seaward edge may alter the nature of the substratum and the rate of sediment accretion and as a consequence are themselves replaced by other species in the process of succession. On stable shorelines where the rate of accretion is low, the zonation characteristic of mangrove communities becomes compressed into a relatively narrow fringe between the marine and terrestrial communities. In actively accreting areas mangrove communities are more extensive and the individual zones, particularly the seaward, pioneer zones, are wider.

Zones subjected to differing degrees of salt water inundation may be divided into five major classes:

1) areas inundated by all high tides;

2) areas inundated by all medium high tides;

3) areas inundated by all normal high tides;

4) areas inundated by spring tides; and

5) areas inundated by exceptional high tides.

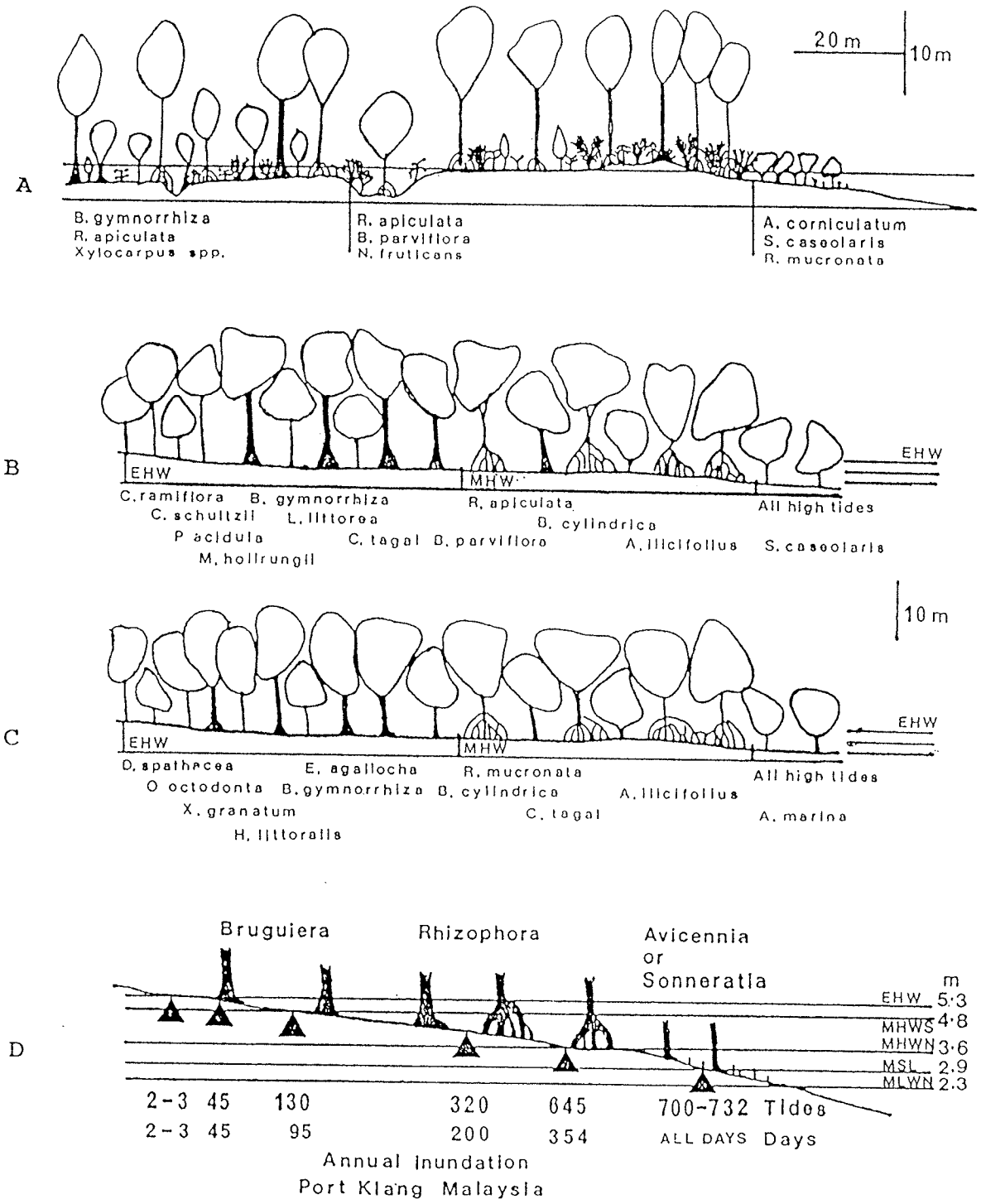
The most salt-water resistant mangroves are those capable of withstanding inundation of their root systems by all medium high tides and include members of the genera *Avicennia* and *Sonneratia*. Areas inundated by normal high tides are characterized by *Rhizophora* while *Bruguiera* is found only in those areas inundated by spring tides. In New Guinea, in areas inundated only occasionally the mangrove community is dominated by *Bruguiera gymnorrhiza* and *Rhizophora apiculata*. In areas of low rainfall and low freshwater runoff into the landward side of the mangrove system, hypersaline conditions may occur characterised by scrubby mangrove growth which grades into halophytic saltmarsh communities. Profile diagrams for mangrove communities in various areas of the Indo-west Pacific are presented in Figure 7. Whilst the species involved may differ in different geographic locations, similar generic patterns are apparent in all profiles.

2.7 The Gulf of Papua: A case study of mangrove formations and zonation

As a consequence of the geographic extent of the Gulf of Papua and the sub-regional and local variation in geomorphic and hydrological factors, several of the classes of terrigenous

Figure 7. Zonation of mangroves in relation to sea level, salinity and hydrological gradients in the Indo-west Pacific (from various sources)

a) Tidal plains, Kikori, Papua New Guinea;
b) Seaward edge, alluvial plains, Papua New Guinea;
c) Sheltered river edge zonation, Purari, Papua New Guinea,
d) major zones in relation to tidal inundation, Port Kalang, Malaysia.



sedimentary coasts detailed by Thom (1982) and Galloway (1982) (Figure 2) can be recognised (Figure 5). Estimates vary of the extent of mangrove forest in the Gulf Province of Papua New Guinea. Hillis (1976) estimated that there are approximately 121,500 ha of Rhizophoraceae forest, and 26,730 ha of pure *Nypa* palm. Paijmans (1969), on the basis of Forestry Map No 1373, estimated 134,400 ha of mangrove swamp; 119,800 ha of mixed mangrove swamp forest; 67,400 ha of mixed mangrove-*Nypa* swamps; 48,500 ha of *Nypa* swamp and 156,600 ha of freshwater swamp forest.

The coastal area of the Gulf of Papua appears to have been a region of continuous shallow marine deposition throughout the Mesozoic and Tertiary eras. Limestones, probably of reefal origin and formed in the lower Miocene, are common in the Purari Delta, indicating that at that time the present deltaic area was some distance inland from the present shoreline (Khan, 1974). Middle and Upper Miocene sediments are mainly marls and mudstones with some evidence of emergence and erosion. During the Quaternary period the south western section of the area was subsiding with volcanic eruptions occurring in the east.

Quaternary deposits include facies indicative of alluvial lakes, freshwater swamps, tidal flats and beach plains indicating oscillations between freshwater, estuarine and littoral environments (Ruxton, 1969). A bore-hole sited WNW of Baimuru on the Era River revealed 1700 m of Pliocene and Pleistocene sediments; the thickness of these sediments increases eastward indicating marked subsidence in relatively recent times (APC, 1969). On the basis of such data Thom and Wright (1982) postulated that modern depositional environments are similar to those which have prevailed throughout the area over the last 5 million years. They quoted Ruxton (1969) as follows:

"*....the coastal margin of the (Purari) delta area is subsiding in association with regional crustal downwarping but the coastline is actually advancing seawards because the deposition rate from the Purari drainage is so great (Ruxton, 1969).*"

The Gulf of Papua (Figures 4 and 5) constitutes a substantial sector of the central southern coast of Papua New Guinea and is traversed by several major rivers. To the east, the Purari has an extensive deltaic system with three major river dominated distributaries. Both the Pie and Era Rivers in the central section of the area have lower flows than the Purari and tend to be more tidally influenced. The western end of the Gulf is dominated by the Kikori, Omati and Turama Rivers with relatively low flow rates and tidally dominated estuarine systems. The deltaic complex of the Purari-Kikori exhibits many of the environmental and morphological characteristics of the Ganges-Brahmaputra and Irrawaddy Deltas (see Wright *et al.*, 1974). In terms of tidal range and wave regime all three complexes are similar, and the discharges of the Purari and Irrawaddy rivers are comparable (Thom and Wright, 1982).

To the east of the region the shoreline is composed of a narrow plain (1-2 km wide) of beach ridges fronting freshwater swamps which merge into alluvial plains with locally accumulating peats in areas of poor drainage. Thom and Wright (1982) suggested some westwards reworking of medium to fine sands (Figure 5). The Purari deltaic plain has well developed levees up to 2 m high along the main channels in its freshwater reaches. Aerial photographs reveal a mozaic of freshwater swamps, swamp forest and rainforest on the elevated areas.

The lower deltaic plain is characterised by brackish water conditions at least occasionally grading into the more saline conditions of the less active distributary channels. In distributary channels where river flow dominates the aquatic environment (e.g. the Ivo-Urika), the morphology of river mouths changes from year to year with consequent changes in the patterns of distribution of sand and smaller particles and dynamic changes to the balance of erosion and accretion. It is common therefore to encounter sections of coastline where mature mangrove forest is being steadily eroded owing to local changes in patterns of sediment deposition.

The western sector of the Gulf Province coast is composed of an extensive complex of funnel-shaped estuaries and deltas dominated by tidal processes, with channels becoming moderately sinuous upstream (Wright *et al.*, 1973) and mud-laden waters being circulated by tides leading to vertical accretion of mangrove-covered tidal flats. Linear tidal ridges extend offshore to a depth of 40 m. In tide dominated estuaries such as those of the Omati, flow rates are low, typically between 0.25-0.5 m sec^{-1} also typically reversing with the tide (Thom and Wright, 1982). Generally such channels are deeper (10 m) than river dominated ones (3-4 m).

Along the southern coast of New Guinea the tides are semi-diurnal and the range is around 2 m. In areas of the Gulf coast tidal ranges are detected at considerable distances inland. For example 15 km inland from the confluence of the Wame and Pie rivers, the river has a tidal range of 150 cm, whilst the Pie River itself is tidal almost to the foothills, a condition which is quite typical of the majority of the creeks and rivers of the western and central sections of the Gulf fringe.

The whole of the geomorphically defined lower deltaic plain of the Purari is dominated by mangrove forest of different formation types. Petr and Lucero (1979) have used the distribution of *Sonneratia caseolaris* to plot the limits of saline influence in the Gulf mangrove and swamp communities. The landward extension of this species corresponds with the lowest extension of the freshwater reed, *Phragmites karka* and the landward extension of a particular (unidentified) estuarine *Pandanus* species. The range of interstitial water salinities near the boundary of the lower deltaic plain is between 1 and 7.5 ‰ (Petr and Lucero, 1979). Thom and Wright (1982) accepted that this biological boundary corresponds to the geomorphological boundary between the upper and lower deltaic areas. Hutchings and Saenger (1987) in reviewing the data on salinity tolerance and influence on mangroves noted that congeneric "pairs" of high and low salinity tolerant species were apparent among Australian species. On the basis of distributions New Guinea "pairs" may be added to this list (Table 3).

Mangrove zonation for the Kikori River area has been described in detail by Floyd (1977) and for the Purari Delta by Cragg (1983). Paijmans (1969) recognised 5 major associations in the area including:

- scrub dominated by *Avicennia*;
- woodland dominated by *Bruguiera* interspersed with *Rhizophora* and a wide variety of other species;
- *Nypa* association;
- low forest predominantly of *Sonneratia* and *Avicennia*; and,
- a mid-height association predominantly composed of *Rhizophora* with some *Bruguiera*.

Table 3. Inferred salinity tolerance of sympatric congeneric mangrove pairs based on their distribution within mangrove stands in the Port Moresby area of Papua New Guinea. (Hutchings and Saenger, 1987).

Seaward species	Landward species
Avicennia eucalyptifolia	*Avicennia alba*
	Avicennia rumphiana
*Bruguiera gymnorhiza**	*Bruguiera cylindrica*
*Ceriops tagal**	*Ceriops decandra**
*Rhizophora stylosa**	*Rhizophora apiculata**
	Rhizophora larmarckii
	Rhizophora mucronata
*Sonneratia alba**	*Sonneratia caseolaris**
*Xylocarpus australasicus**	*Xylocarpus granatum**

(* species for which salinity tolerance data from Australia confirm low or high tolerance level)

Approaching a Gulf mangrove stand from the sea the first zone encountered is dominated by *Sonneratia alba* which may be inundated on a daily basis, with the congeneric *Sonneratia caseolaris* replacing it in the tidal creeks. On most mangrove dominated sections of the New Guinea coastline, the seaward zone normally includes *Avicennia eucalyptifolia* (= *marina* Frodin & Leach, 1982) on the seaward edges, being replaced by *A. alba* along the mouths of tidal creeks. This zone in accreting areas may extend up to 750 m inland and both species are present in the Gulf associations.

Rhizophora forests develop behind the pioneering species mentioned above with *R. mucronata* being more seaward than *R. apiculata*. In this zone the substrata are inundated by normal high tides. Landward of this zone in the areas inundated by spring and exceptionally high tides the community is dominated by *Bruguiera*, whilst in some areas *Ceriops* thickets form a landward fringe to the mangrove community. *Ceriops* thickets frequently develop in areas of low rainfall where the freshwater inputs to the landward side of the mangrove stands are limited. This in combination with high evaporation rates results in super saline soil conditions and the development of salt pans. The saltmarsh vegetation of Australia and some areas of the wider Caribbean region develop in similar environments where the rainfall inputs are even lower, than in the humid tropical regions of the Indo-west Pacific.

In the fringing mangroves of the Gulf of Papua the *Nypa* association occurs in areas alongside tidal streams flooded by the highest Spring tides and the species is therefore an indicator of brackish water conditions. Any transect from the seaward edge to the landward side of the mangrove community, whilst it might conform to the general pattern described above will be affected by local conditions of accretion, erosion, freshwater inputs and tidal influences. No single transect profile would suffice therefore to describe the total area of the Gulf mangroves. Where the lower deltaic fraction of the Purari River estuary is dominated by massive freshwater inputs zonation differs from the central and western areas where the creeks and river mouths are influenced more by tides and salinity regimes.

2.8 Mangrove faunas of subsistence and commercial importance

Mangroves are considered to be important nursery areas for fish and prawns (Birkeland, 1985; Robertson & Duke, 1987). Haines (1983) states that around sixty three estuarine, fifty nine marine, and fifteen riverine fish species may be found as adults in the Purari and Kikori mangrove areas. Juveniles of thirty five estuarine, twenty one marine and five riverine species have also been found in the estuarine areas. These data suggest that the mangrove areas support a characteristic fish fauna in addition to forming a marginal habitat for more marine or riverine species. Haines (1979; 1983) found that the main breeding season as judged by gonad condition was October to December, the end of the wet season in the area.

Mangroves are known to play an important role world-wide as nursery areas for Penaeid prawns (Le Reste, 1973; Tabb et al, 1962; Mohamed & Rao, 1971; Walker, 1974; Staples, 1980a, 1980b; MacNae, 1974; Frusher 1983; Gwyther, 1983; Robertson, 1988; Robertson & Duke, 1987; 1990) and throughout the Indo-west Pacific substantial commercial prawn trawling operations are associated with areas offshore from mangrove systems. MacNae (1974) demonstrated the relationship between mangrove area and yield of prawns in 1971 for areas off the east coast of Africa. A general relationship is apparent between the size of the nursery areas and the resultant fishery, suggesting that factors regulating the survival of juveniles in the mangroves are important in determining the size of the adolescent and breeding populations (Robertson, 1988).

In the Gulf of Papua, the prawns spawn in the open sea with females of *Penaeus merguiensis* producing up to 300,000 eggs. In the plankton, nauplius, mysis and zoeal stages develop, gradually migrating inshorewhen the post-larval prawns settle on the bottom two to three weeks after hatching (Frusher, 1983; Gwyther, 1983). As juveniles the prawns enter the estuarine and mangrove systems remaining for a few weeks to several months, migration of sub-adult prawns back out to the off-shore spawning grounds often accompanies heavy seasonal rainfall. Different prawn species may be found in different sections of the Gulf mangroves, apparently correlated with differing salinity preferences. *Penaeius merguiensis* being more abundant in the Aird Delta in salinities of between 15 and 20 ppt, *Metapenaeius demani* being more abundant in the less saline areas of the Purari Delta at salinities of less than 5 ppt; and *Metapenaeus eboracensis* dominating catches in the intermediate salinity ranges (Frusher, 1983). In the freshwater reaches of the Delta, penaeid prawns are replaced by carid prawns in particular the giant freshwater prawn *Macrobrachium rosenbergi,* which unlike the detrital feeding penaeids tends to feed on worms, insects and small crustaceans (Ling, 1969).

Mud crabs, *Scylla serrata* undergo a similar life cycle, the adults undertaking a seaward migration after mating in the mangroves. Berried females are taken at depths between 7 and 70m in the offshore prawn trawls, and are known to be preyed on by tiger sharks in the Mozambique channel (Crosiner, 1962). The eggs are carried for around 17 days (Arriola, 1940) before hatching, when the zoea larvae use ocean currents to return towards the estuarine environment. Within the mangrove systems of the Gulf of Papua, *Scylla serrata* appears to be confined to areas of saltwater penetration and in the Purari Delta its population density reaches 21.4 crabs ha^{-1} twice that found in the Aird Delta (10.4 crabs ha^{-1}).

The fish faunas of mangrove and estuarine areas are interesting and varied (Robertson & Duke, 1990) and in New Guinea include a large number of "mud-feeding" species (Haines, 1983). Haines (1983) and Roberts (1978) noted for the Purari and Fly Rivers respectively that congeneric pairs of species tend to replace one another in the riverine and estuarine environments (Table 4).

Table 4. Congeneric fish pairs in the Purari River and estuary (From Haines, 1983).

Freshwater	Delta & Estuary
Carcharinus leucas	*C. glyphis*
Thryssa scratchleyi	*T. hamiltoni*
Arius acrocephalus	*A. leptaspis, A. proximus*
Cochlefelis sp.	*C. danielsi*
Nedystoma dayi	*Nedystoma* sp.
Hemipimelodus crassilabris	*Hemipimelodus* sp.
Stenocaulus krefti	*S. strongylura*
Zenarchopterus novaeguineae	*Z. brevirostris*
Aseraggodes klunzingeri	*Aseraggodes* sp.
Liza oligolepis	*L. vaigensis; L. dussumeri, L. tade*
Valamugil buchanani	*V. seheli*
Ambassis interruptus	*A. nalua; A. macracanthus*
Hephaestus fuliginosus	*H. jarbua*
Nibea sp.	*N. semifasciata*
Glossogobius celebius	*G. giurus*
Oxyeleotris fimbriatus	*O. urophthalmus, O. lineatus.*

Table 5. Number of fish species in each ecological zone, eating different food types (After Haines, 1983). The estimates of species numbers in the coastal region are probably incomplete.

Food type	Upper delta Freshwater	*Sonneratia*	*Nypa*	Lower delta Mangrove	Coastal Zone
Omnivores	2	2	2	2	3
Fish	7	8	10	+15	+14
Molluscs	4	4	4	4	6
Prawns	14	15	20	20	15
Crabs	0	0	8	11	6
Insects	3	+4	+4	+4	0
Fruit	2	2	2	3	3
Plant	0	1	1	2	2
Detritus	4	+5	+9	+9	+13
TOTAL	36	+41	+60	+70	+62

Haines (1979; 1983) reports approximately forty one species of fish including nine ariid catfishes from the *Sonneratia caseolaris* zone of the Purari mangrove system compared with more than sixty from the *Nypa* association and more than seventy from the lower mangrove zone of the delta. Species diversity appears to decrease inland from the coastal reaches of the mangroves. In general the number of prawn, crab and detrital feeding species was higher in the mangrove zones than in the river itself and the freshwater reaches of the delta, indicating the relative importance of these animals in the mangrove community.

Carid prawns are the dominant food source for carnivorous fishes in the freshwater and upper estuarine zones, being replaced by penaeid prawns in the lower estuarine and coastal zones. Table 5 provides comparative data on the numbers of fish species in each trophic category in the different ecological zones of the Lower Purari River and its Delta. A notable characteristic of this fish faunal assemblage is the scarcity of herbivores and the absence of planktivores.

2.9 Vertebrates of conservation concern

In general the vertebrate faunas of mangroves have been much neglected. A number of birds are known to utilise mangroves as their primary habitats, and it has been suggested that in Australia the avifauna of mangroves developed as progressive aridity restricted the extent of terrestrial forest formations (Schodde, *et al.*, 1982). Several fish eating species, including kingfishers and sea eagles, represent top carnivores in the mangrove food web. In the south Asian region several of these avian piscivores are considered threatened and the Sundarbans mangrove forest of Bangladesh and India forms one of the last refugia for the Bengal tiger. Amongst the mammals several rats and smaller carnivores utilise mangrove habitats although none appear to be restricted to this habitat. Bats may utilise mangroves both as feeding areas and as roosts, whilst goannas and larger lizards of several species inhabit the swamps feeding on crabs, turtle eggs and assorted invertebrates. A number of snakes such as *Fordonia leucobalia* in Australia and New Guinea are restricted to the habitat, some of which are specialised for feeding on invertebrates. Several geckos and smaller lizards occur in mangrove habitats, one at least being confined to this habitat in the Port Moresby area of Papua New Guinea (Pernetta & Black, 1983).

Perhaps the most significant non-fisheries elements of the mangrove fauna in Melanesia from a human perspective are the crocodiles and turtles, which are hunted for food and skins. Of the seven freshwater turtles in New Guinea several occur in brackish and saline estuarine environments, whilst the mangroves and freshwater swamps of the south coast of New Guinea are the centre of distribution for the pitted shelled turtle *Carettochelys insculpta* which feeds at least in part on mangrove propagules and moves up-river to suitable sand banks to lay eggs (Pernetta & Burgin, 1980). Crocodiles, both saltwater (*Crocodylus porosus*) and freshwater (*Crocodylus novaeguinea*), are the top aquatic predators of the mangrove system being largely piscivorous as adults, although as hatchlings prawns form a major component of their diets. *Crocodylus porosus* was once much more widespread in mangrove habitats throughout south east Asia and Island Melanesia. In part, over hunting for its skin has caused the decline (Burgin, 1980), although the general loss of mangrove habitats throughout the region must also have contributed to restriction of its present distribution.

3. Potential Impacts of Climate Change and Sea Level Rise

3.1 Scenarios of global change

The fact that global mean surface temperature has risen around 0.5 °C (0.6 +/- 0.2 °C) over the last century is now widely accepted (Houghton, 1991). Similarly measurable increases in greenhouse gas concentration have occurred over the same time period, and recent evaluations of global sea level change suggest that the current average rate of rise is approximately 1.5 mm yr^{-1} (Raper *et al.*, 1990; Stewart *et. al.*, 1990).

Climate models suggest that the observed changes in global mean surface temperature and sea level could be the result of the increased concentration of greenhouse gases in the atmosphere which result from anthropogenic activities including increased agricultural production, deforestation and the burning of fossil fuels. Whilst the similarity in trend between these three sets of observations supports the greenhouse theory, a causal relationship is not proven and the anthropogenic impacts on global climate remain a scientific hypothesis.

Under the Intergovermental Panel on Climate Change (IPCC) Business-as-usual scenario for future greenhouse gas emissions global mean surface (air) temperatures are projected to rise by around 0.3 °C per decade, a rate of increase greater than that seen over the past 10,000 years (Houghton, 1991). This rate would lead to a likely increase in global mean temperature of 1 °C above the present value by 2025 and of 3 °C before the end of the next century accompanied by a rise in global mean sea level of around 6 cm per decade over the next century. The 1992 revision suggests a likely lower rate of change to both global mean temperature and global mean sea level. The IPCC process of evaluating scientific understanding, impacts and response measures is on-going, and hence it is to be expected that these estimates will change in any future assessment. It must also be recognised that these scenarios refer to changes in global mean values and that the actual values of temperature and sea level at any particular site may differ considerably from these estimates due in part to site specific orographic climate effects; geomorphological processes such as land subsidence; and local sources of anthropogenic change such as groundwater extraction. The IPCC further suggests that changes to global mean temperature will be greater at higher latitudes.

Present areas of uncertainty in climate modelling and prediction include aspects of the role of the ocean; the role of upper atmosphere water vapour and clouds; regional level scenarios; and, the climatic influences of natural factors unrelated to greenhouse gases. Such areas of scientific uncertainty result in limitations to predictions of impact and also place widely separated upper and lower planning bounds on impact scenarios. Assuming that greenhouse gas concentrations continue to rise, some global warming may be expected during the next century. The magnitude of the human induced greenhouse gas warming and the overall extent of the global changes which will occur are still ill-defined.

A major constraint to impact assessment in biological communities such as mangroves is the absence of accurate scenarios of future rainfall, both seasonality and total quantity. Not only is rainfall a major determinant factor in limiting the distribution of terrestrial biomes on a global scale it has major effects on a local scale through its influence on processes such as water and sediment flux from land to near-shore waters. Without some detailed assessment of such changes on a local and sub-regional scale precise assessment of impacts at single locations is not possible.

Polutikof *et al.* (1992) have developed regional and sub-regional scenarios of change for the Mediterranean area through taking the equilibrium response predictions for relevant grid-points of four Global Circulation Models (GCMs) to develop composite scenarios, since none of the four GCMs was found to be consistently better than any other at predicting present climate. High resolution scenarios were then developed by relating local and large scale regionally averaged values of temperature and precipitation. Whilst Polutikof *et al.* (1992) have reasonable confidence in the future scenarios of temperature so developed their confidence in future scenarios of rainfall is less strong. Despite such reservations the development of similar regional and sub-regional scenarios is vital if impact assessment is to be improved to the point where it is of immediate value for planning and management of systems such as mangroves, coral reefs and coastal zones in general.

3.2 Large scale changes to distribution of the mangrove biome

Given that mangrove ecosystems have their centre of distribution in the tropics and sub-tropics and that present limits to their latitudinal distribution appear correlated with temperatures, both air and sea surface water temperatures, extension of the global range of such ecosystems to higher latitudes might be expected under warmer climate conditions.

In general terms the present latitudinal limits to mangrove distributions are not identical north and south; nor on the east and west sides of continental landmasses. Greatest present latitudinal range of mangroves along the landward margins of the ocean basins is seen on the eastern shores since currents along the continental shelves in these regions generally pass from the equator towards the poles. In general terms the opposite pattern pertains to the western continental margins. On the western margins of Africa and Latin America extensive zones of upwelling result in cooler surface waters approaching closer to the equator, a point noted by Chapman (1975) who also noted that the northward movement of coastal currents in the southern hemisphere limits the dispersal southward of mangrove propagules. The present 24 degree isotherm (Figure 1) displays this general pattern extending further into higher latitudes on the eastern than the western continental margins. Where the temperature of coastal waters is largely determined by upwelling or cool currents flowing from the poles towards the equator then, provided that no major changes in basin scale ocean movements occur, the latitudinal extent of mangrove distribution is unlikely to change.

At the present latitudinal limits of their distribution mangroves represent low diversity, relict populations or communities often with a single dominant species of scrubby growth form. Extension of range into areas which become climatically suitable in a warmer world will involve two interacting factors, the first being changes in species growth and reproduction. As conditions at a particular site approach more closely the optimum conditions presently occurring towards the centre of the biomes present distribution, individual species vigour and reproductive rates can be expected to increase. Improved vigour in presently marginal populations will enhance their competitive advantage over other vegetation types for which the conditions cease to be optimal.

The second factor affecting long distance extension of range will be the nature of coastal currents which will affect the dispersal success of propagules produced near the present limits of individual species ranges. In western continental margins where surface currents generally pass towards the poles a faster rate of range extension may be anticipated than on the east since propagules will naturally be moved north and south along these margins.

It is to be expected that as individual species ranges are extended, species diversity will increase in mangrove communities currently outside the centre of biome distribution. In the Caribbean and Atlantico-west Pacific sub-region changes in diversity may be less extensive and less obvious, given the more limited range of mangrove species present (seven species). Changes to species diversity will therefore be more obvious at the present margins of their range in this region. In contrast warmer climates, will effectively increase the latitudinal extent of conditions now found in the "core" of mangrove distribution in the Indo-west Pacific and Malesian sub-regions. Changes in species composition and diversity may be more obvious in this region given that the cline of diversity is greater having some thirty seven species in the central tropical belt and only two or three at high latitudes.

Increased species diversity at the community level will add to the competitive ability of mangrove communities as a whole. Outside the present latitudinal limits for mangroves, comparable sedimentary coastal environments are generally occupied by saltmarsh vegetation. It is likely, given the more herbaceous nature of the vegetation in these communities that mangroves will out-compete such species in the medium to long term and that a gradual replacement of saltmarsh vegetation by scrubby mangrove, first of *Avicennia* and later of *Rhizophora* may be expected to occur.

The rate at which the changes outlined above might be expected to occur cannot be predicted at present since, not only can the rate of climate changes themselves not be predicted accurately but also, data on dispersal and survival rates of mangrove propagules, on the ecophysiology and on the life history of many mangrove species are imperfectly known. It seems likely however that general range extension will not occur in all areas but will be concentrated along the eastern continental margins rather than on the western margins. It is also assumed that the prevailing patterns of oceanic currents will remain essentially unchanged. Should patterns of ocean currents change either on a basin or sub-basin scale then unexpected changes to the present distribution of the mangrove biome may occur.

3.3 Sub-regional and local changes in mangrove communities

3.3.1 Mangroves in alluvial and tidal plains: The Kikori and Purari rivers, Gulf of Papua, Papua New Guinea

Whilst the global distribution of mangroves is likely to be most affected by temperature changes in the long term, shorter and medium term changes can be expected in individual mangrove communities as a consequence of changes to other physico-chemical environmental factors. Since mangrove ecosystems are, broadly speaking "intertidal" any changes to sea level will automatically affect all mangrove communities regardless of their geographic location. The first two classes of mangrove geomorphological settings namely alluvial and tidal plains are well illustrated by the Purari and Kikori mangrove systems of the Gulf of Papua.

In the Purari delta low tidal amplitude and high river discharge of water and sediment dominate the system. Pickup (1983) has estimated that the mean discharge of the Purari is around 2,360 m^3 sec^{-1} with peaks in excess of 10,000 m^3 $sec^{-1,}$ while mean discharge from the Kikori to the west is 1,500 m^3 sec^{-1}. The Purari delivers 88.6 million m^3 sec^{-1} of sediment to the head of the delta of which 6% is sand, 48% is silt and 46% is clay (Pickup, 1983). The deltaic plain can be divided into an upper freshwater system with marked levees up to 2m in height while the lower system is ephemerally brackish grading into increasingly saline areas in the less active distributary mouths (Thom and Wright, 1983). The western complex of tidally dominated funnel-shaped estuaries displays linear tidal ridges extending offshore and extensive tidal flats on which muds are deposited under tidal action.

A simplistic first approximation of the impacts of a given rise in sea level can be made merely by shifting the shoreline an appropriate distance inland and replotting mangrove zonation in relation to the new conditions of elevation. Such an exercise was performed for the mangrove ecosystems of the Gulf of Papua by Pernetta and Osborne (1990) who concluded that in the case of the extensive low-lying Purari delta area significant compression of mangrove zonation was unlikely to occur even under extreme scenarios of change. In contrast the central Gulf and Kikori delta mangrove areas were likely to undergo substantial alterations to their patterns of zonation since the break in slope occurs closer to the existing shoreline in these areas and allochthonous sediment inputs are largely derived by long-shore drift.

Areas of mangrove growing in deltaic and tidal coastal plains are likely, under conditions of rising sea level to undergo erosion and loss from the seaward edge. Simultaneously as saline conditions penetrate further inland the mangroves of the inner margins will begin to replace the terrestrial and freshwater swamp vegetation. The entire ecosystem may therefore be viewed as "migrating" inland, although the rate of landward extension may not be the same as the rate of loss of pioneer mangroves from the seaward edge of the system. The limitations to such landward "migration" under natural conditions will be reached when the inland slope exceeds that of the seaward edge. At this point erosion of the seaward edge will outpace inland colonisation which will eventually cease and the mangrove system will be progressively compressed becoming converted ultimately to a mangrove community typical of a drowned bedrock coast.

As noted by Pernetta and Osborne (1990), this model is indeed simplistic, involving assumptions about the rate of various processes which may or may not be valid for any individual location. As noted above the mangroves of the Purari delta are actively prograding and the sediment supplies from the Purari River not only contribute to this active seaward migration of the mangroves at the seaward fringe of the delta but also to the continued relative stability of the tidal mangrove system of the Kikori delta area to the west. If one assumes that both rainfall and erosion rates in the catchment of the Purari river remain the same and that the current rates of crustal downwarping and sediment compression also remain the same, then under conditions of rising sea level the rate of progression of the Purari delta may be expected to decrease. Simultaneously supplies of sand to the Kikori delta area derived at present by long-shore drift from the Purari will be diminished and regression of the mangrove system in this area may be expected to accelerate.

Approximate values for existing rates of change in this area can be derived from the thickness of existing sedimentary deposits and the extent of the depositional plain. As noted above, boreholes indicate the deposition of around 1,700 m of terrigenous materials over a 5 million year period resulting in a depositional plain of between 30 - 60 km wide. Vertical accretion rates are approximately equivalent to 0.34 mm yr^{-1} and horizontal progression rates over the same period are between 60-120 cm yr^{-1} averaged over the whole Purari delta front. Obviously averaging values over such extended spatial and temporal scales provides only generalised models for the processes of interest in the present analysis.

Thom and Wright (1983) discuss the geomorphology of the Purari delta in some detail; they note the paucity of data and the need for further field data to validate their conclusions. Nevertheless they suggest three possible geomorphological models to explain the available data. The existence of an extensive sand sheet of between 8 - 40 m depth occurs in the lower delta area overlain by organic blue clay of between 10 - 15 metres thickness. In the upper delta near the junction of the three main distributaries coarse blue sand of up to 30 m is overlain by around 3m of blue clay. Thom and Wright (1983) suggest that the coarse blue sands represent fluvial deposits during a period of lower sea level and the blue clays represent deposition in backplain/ levee environments. At the delta front, the sand sheet recedes during the postglacial marine transgression, and progrades seaward during the subsequent 'stillstand'. Conservative estimates of vertical accretion rates over the last 10-15 thousand years would therefore be of the order of 0.66 -1 mm yr^{-1} with maximum rates of around 1.5 mm yr^{-1}. On the basis of data from radiocarbon dated wood taken from a 12 m cored hole at Mapaio, Thom and Wright (1983) estimated a vertical accretion rate of 1m in slightly less than 1000 radiocarbon years. It would appear therefore on the basis of this evidence that the Purari delta is capable of maintaining its present form under current rates of relative sea level change.

Under conditions of accelerated sea level rise gradual recession of the shoreline is likely to occur. To the west of the Purari, on the other side of the Gulf the Kikori, tidal estuarine system is dependent on long-shore drift carrying sediments from the seaward edge of the Purari delta frontin order to maintain its present form. At various points along this western shoreline active recession is already occurring, (Cragg, 1983: Thom & Wright, 1983; Liem & Haines, 1977). Floyd (1977) estimated that at one site recession was occurring at a rate of 20 m a year. Recession of the mangrove front in this area is likely to proceed at a faster rate under future

scenarios of sea level rise. It is therefore in this area of the Gulf that changes in zonation, species distribution and the stability of the mangrove ecosystem are most likely to become initially visible.

As noted above the relative changes to the major mangrove zones are unlikely to be equal, regression of the seaward *Sonneratia, Avicennia* zone is likely to occur at a faster rate than landward migration of the *Rhizophora* and *Bruguiera* zones. Hence differential loss or reduction in the abundance of species in the pioneer mangrove zone is likely to occur. In the Gulf of Papua, propagules of pioneer species such as *Avicennia eucalyptifolia* and *Sonneratia lanceolata* appear capable of withstanding longer periods of inundation than those of other species (Floyd, 1977). The vertical pneumatophores of these species modify local currents and promote further sedimentation (Spencely, 1977) such that once the level of the substratum has risen, propagules of *Rhizophora* species and later *Bruguiera* become established. Under erosional conditions this succession does not occur and indeed the extent of the *Sonneratia/ Avicennia* pioneer community is generally limited in the tidal Kikori estuary. Cragg (1983) also notes that in the case of the mangroves at the mouth of the Angabunga delta to the east of the Purari, changes to the course of the river resulted in reduced sediment inputs to the original river mouth. In this area the shoreline has receded such that the seaward fringe of pioneer species has completely disappeared and the inland mature forest of *Rhizophora apiculata* is being steadily eroded.

Changes in the overall extent of mangrove ecosystems combined with changes to the relative extent of different zones could dramatically alter the productivity of commercial and subsistence fisheries since the distribution of individual fish and prawn species reflects the gradients of salinity occurring through the mangrove system and the zonation and productivity of the entire system.

Few empirical data for differential changes in the extent of individual mangrove zones under conditions of rising sea level are available in the literature (Ellison & Stoddart, 1991). Evidence for analogous changes does exist in the case of temperate saltmarsh communities outside the tropical and sub-tropical range of mangroves. Mehta and Cushman (1989) who studied the consequences of a 1 m relative rise in sea level which has occurred over the last century in Barataria Bay, Louisiana have demonstrated that not only has the Bay increased in surface area by between 10 - 15% at the expense of neighbouring wetlands, but also, that the distribution of ecotones has shifted landward. Smith and Kitchens (1989) have further demonstrated that an equal landward shift of all ecotones has not occurred in the case of the Savannah River marshland vegetation under changed tidal and salinity regimes which mimic the changes predicted to occur under future sea level rise scenarios. Although the overall extent of the saltmarsh community was not changed and this ecotone merely shifted inland the tidal freshwater community did not shift upriver and the extent of this community has consequently been greatly reduced (Latham *et al* cited in Smith and Kitchens, 1989). Applying the saltmarsh analogy to the mangrove and swamp forest ecosystems of the Kikori delta one might therefore predict a compression of the *Nypa* freshwater and inner mangrove zones.

3.3.2 Mangroves in barrier lagoons, composite coastal plains, drowned bedrock and coral coasts

Where mangrove systems occur in lagoons behind hard rock barriers (Figure 2) the impacts of a rising sea level will be less than in the case of those occurring in lagoons behind beach ridges of allochthonous material. The extensive mangrove systems of the Murik Lakes in the composite alluvial plain of the Sepik River in northern Papua New Guinea (Figure 2) is an example of this latter class. The Sepik Ramu basin was occupied by an extensive, shallow inland sea which invaded the lower basin during the early Holocene (Chappell, 1990). Old shorelines for 6,000 and 2,000 years ago demonstrate clearly the rapid marine regression which occurred as a consequence of high sedimentation rates when sea levels stabilised some 6,000 years ago. On the basis of direct sediment gauging and core analysis Chappell (1990) estimates that deposition in the Sepik Ramu basin has been equivalent to 0.3 m per century (3 mm yr^{-1}). This is an upper estimate, equivalent to deposition of the bulk of the sediment derived from the catchment within the basin itself and minimal losses to the near-shore marine environment. Unlike the Gulf of Papua the offshore area adjacent to the mouth of the Sepik River drops rapidly, there is no continental shelf and the extensive shallow sub-aqueous delta systems characteristic of the southern coast do not exist.

Given this offshore profile further progression of the delta system is not possible and the Murik lakes owe their existence to the presence of beach ridge systems. Hughes and Bualia (1990) conclude that these unconsolidated beach ridges would be susceptible to erosional loss should sea level exceed 3 mm yr^{-1}. At present their integrity is maintained by long-shore drift of sediments carried from the mouth of the Sepik River to the East. Loss of mangrove systems would therefore occur in the Murik Lakes area before it occurred in the area of the active Sepik mouth.

The mangroves of drowned bedrock coasts generally consist of a narrow fringe without marked zonation. The extent of this fringe generally depends on the prevailing winds, wave energy and slope of the shore. Where the beach is backed by near vertical cliffs the zone, where present, is much less extensive than in areas where scree slopes drop down to the beach. In coral island environments either raised limestone platforms or motu (atollic islands composed of bioclastic sand and rubble, with an elevation of under 4m) mangroves are frequently most extensive in the lee of islands; behind raised storm beaches; or fringing hypersaline lagoons where these occur.

Ellison (in press) and Ellison and Stoddart (1991) have discussed *in extensio* the potential impacts of rising sea level on the mangroves of low island environments. They conclude that in areas where allochthonous sediment sources are small or absent, mangrove systems may undergo catastrophic collapse under scenarios of accelerated sea level rise. Ellison (in press) in reviewing historical data for low island mangrove systems concludes that such systems can keep pace with an estimated rise of 8 cm per century but that at rates in excess of 12 cm per century the community is incapable of maintaining itself. In Tongatapu a low limestone island, Ellison (1989) found that the mangrove community was inundated by formation of a lagoon around 5,000 B.P. as relative sea level rose in excess of 12 cm a century, present rates of vertical accretion through peat accumulation are estimated at 7.7 cm a century. In Grand Cayman mangrove peat accumulation during the late post-glacial period of gradual submergence has

equalled 8.8 cm a century whilst at Hungry Bay, Bermuda, peat accumulation over the same period was equivalent to 10.6 cm a century (Ellison, in press).

These data are of more general importance within the context of the potential responses of mangrove ecosystems to sea level rise. In general, mangrove communities of coral coasts and low island environments; have low species diversity; are of small areal extent (in both absolute and global terms); are often exposed to moderate wave energy, at least seasonally; and, are reasonably well flushed. The values for vertical accretion discussed by Ellison (in press) therefore represent the minimal vertical accretion rates for mangroves based almost entirely on accumulation of autochthonous material. Ellison (in press) also notes that in the high islands of Fiji, and in Kosrae, Caroline Islands accretion rates measured by different authors varied from 3 to 18.8 cm a century (Fiji and Caroline islands around 11 and, Samoa around 13 cm per century). On coral coasts allochthonous sediments are largely bioclastic carbonates which contribute little to the build up of acidic mangrove soils.

As discussed by Chappell (1990) in relation to the effects of potential sea level rise on tropical riverine lowlands a primary consideration in assessing the potential impacts and system responses to future sea level rise is the sediment flux from the catchment of the river system concerned. Whilst it might be argued that from the perspective of the response of the mangrove ecosystem, allochthonous sediment inputs represent the determining factor, this is not necessarily the case for all classes of mangrove formation. Mangroves on drowned bedrock coasts for example already exist in environments with low sediment inputs, their species composition is often different from that of more extensive systems and the trees themselves may grow on rock pavements, or, in scree and shingle rather than in the more normal soft sediment environments characteristic of low energy depositional shorelines. In the Indo-west Pacific mangroves are not confined to low wave energy depositional shorelines although the greatest development of the ecosystem occurs in such environments.

3.3.3 Mangroves and other factors of climate change.

No review of the possible responses of mangroves to climate change and sea level rise would be complete without consideration of the potential consequences of changes to a variety of other environmental factors such as increasing CO_2 concentrations; changes in precipitation; alterations to coastal currents and wave climates; and changes in frequency and intensity of episodic meteorological events such as tropical storms.

Most obligate mangroves have a C_3 pathway for carbon fixation during photosynthesis (Clough *et al.*, 1982) and the consensus view is that such plants will increase their productivity under enhanced CO_2 partial pressures. Not only does the rate of photosynthesis increase but reduced stomatal conductance under higher CO_2 levels leads to more efficient water control through reduced transpiration losses. It should be recognised however that alteration to leaf production and subsequent changes to overall plant productivity within a single species also alters the competitive ability of that species. The consequences of such changes at an ecosystem level are therefore difficult to assess since they represent a multi-dimensional, non-linear set of interactions. In terms of the present state of knowledge concerning the ecophysiology of individual mangrove species we are unable to predict with any certainty the consequences of

increased atmospheric CO_2 for individual populations, consequently it is impossible to predict changes in relative competitive advantage between species and hence the potential consequences for mangrove floristics. One consequence of increased CO_2 may be an increase in overall primary production in mangroves and hence an overall increase in litter production and vertical accretion rates. It is unlikely however that such changes will significantly alter the conclusions concerning potential sea level rise impacts discussed above.

Oxygen supply to the roots of many species is increased through pneumatophores which project above the substratum as "knees" or vertical branches. Continued inundation in excess of the diurnal tidal conditions to which mangroves are adapted may prevent the lenticelsfrom functioning resulting in lowered plant oxygen concentrations (Scholander, 1955) anoxia and mortality after varying periods. Harrington and Harrington (1982) document extensive mortality in *Avicennia germinans* and *Rhizophora mangle* following four months of inundation of between 30-40 cm in an area with a natural tidal range of 10-20 cm.

Since mangroves occur in a saline environment they possess various strategies for salt regulation which enable them to exclude, secrete or accumulate salt in order to control their water balance. Mangroves effectively inhabit a physiological desert, hence major structural modifications occur in mangrove leaves associated with the retention of de-salinated water and reduction of transpiration water losses. Most mangrove leaves are xeromorphic, and display low transpiration rates (Lugo *et al.*, 1975; Moore *et al.*, 1972) with transpiration peaking prior to midday and declining throughout the afternoon. In general increases in salinity result in increased respiration, decreased net primary production and consequently decreased growth rates (Stern and Voight, 1959; Ball and Farquhar, 1984a, 1984b).

Litter production has been estimated for *Avicennia* at 1.2-1.5 kg m^{-2} yr^{-1} (Briggs, 1977) for *Rhizophora* mangle at 0.9 kg m^{-2} yr^{-1} (Heald and Odum, 1970) and 0.5 kg m^{-2} yr^{-1} (Golley *et al.*, 1962). In tropical Queensland a figure of 2.8 kg m^{-2} yr^{-1} appears to be the highest value recorded to date (Bunt, 1978; 1982) most values being around 0.5 kg m^{-2} yr^{-1} (Hutchings and Saenger, 1987). Ellison (in press) provides a more extensive tabulation of litter productivity data by species and latitude which suggests a general decline in litter production from around 1 kg m^{-2} yr^{-1} at the equator to around 6 t ha^{-1} yr^{-1} at 36 degrees of latitude.

Seasonal variation in primary productivity is known for several species. Saenger and Moverley (1985) measured seasonal leaf production in nine species of mangroves in Queensland and showed the existence of five classes. Species such as *Aegialites annulata* were practically non-seasonal, whilst species such as *Ceriops* were shown to have slight seasonal increases in leaf production during the summer. Highly seasonal leaf production but non-seasonal leaf loss were characteristic of *Aegialites corniculatum* and *Osbornia octodonta*, bimodal patterns in *Avicennia marina* with minimum leaf production and fall occurring during the flowering season; and highly seasonal species such as *Xylocarpus australasicus* where maximum leaf loss occurs immediately prior to maximum new leaf production.

Whilst litter production may increase, decomposition rates within mangrove peats will also change. General conclusions concerning changes in soils in terrestrial environments are that decomposition of organic matter may occur faster under warmer climates. In the case of tropical

and subtropical inter-tidal mangrove soils a further factor needs to be considered. The pathways for anaerobic carbon catabolism during micro-decomposition differ in saline and freshwater soils. As saline conditions penetrate further inland to previously freshwater backswamp areas behind mangroves then a shift from methano-genesis to sulphate reduction as the dominant micro-decomposer pathway may occur (Smith and Kitchens, 1989). As a consequence of both the rise in temperature and change in decomposition pathway, loss of peat may occur with consequent reduction of elevation in backswamp areas.

Of considerably greater importance for a number of reasons are potential changes to rainfall, both in total volume and in terms of its distribution on a seasonal basis. Not only will changes to total volume and seasonal pattern alter the phenology and productivity of individual mangrove species but such changes will also alter the salinity gradient through mangrove ecotones with resultant impacts on zonation of the ecosystem itself. In addition to the direct effects of changes in precipitation on the individual community changes in rainfall at considerable distance may indirectly affect the coastal community via changes in runoff and erosion from inland catchment areas and hence sediment and nutrient flux within the mangrove ecosystem. It is regrettable that given the present state of knowledge changes in precipitation patterns under future scenarios of temperature cannot be made with any degree of certainty. Although it is generally thought that total precipitation will increase in a warmer world, the sub-regional and local patterns of change must be determined if the potential responses of mangroves to climate change are to be evaluated on a local level.

Whilst the IPCC (Houghton, 1991) assessment suggests that storms may increase in both frequency and intensity, scenarios are far from unanimous in this view. Mangroves, given their shallow root system and coastal location, are susceptible to windthrow and other forms of storm damage, including crown and bole damage and death, where the tree remains standing (Stocker, 1976). Different genera and species display differing abilities to withstand these various forms of damage hence periodic exposure to storms may affect species composition within mangrove stands. In addition to changes in storm frequency and or intensity in areas where such storms already occur, it is possible that the global distribution of storms may change. Clearly, if the zone of tropical storm genesis were to extend to higher latitudes than at present, then the possibility arises that areas never previously affected by such episodic events, may in the future experience storms. It could be argued that natural ecosystems, including mangroves which presently occur outside the zones of tropical hurricane damage would, at least in the short term, suffer greater damage than those which have been subjected to such events in the past.

4. Individual, Population and Ecosystem Responses of Mangroves to Various Components of Global Climate Change and Sea Level Rise

Table 6 provides a general overview of the potential environmental changes which will impact mangrove ecosystems under warmer climates and the possible consequences of such changes for mangroves at species and ecosystem level. This tabulation is not intended to be exhaustive but merely to indicate the level of complexity which results from positive and negative feedback loops characteristic of biological community responses to changes in the physical environment. It is obvious that the response of individual species to single sources of change may be either positive or negative. The combined effect of changes to several variables may be either positive, neutral or negative depending on the magnitude of the changes to individual variables and the nature of the individual species response. Similarly taking the analysis to an ecosystem or community level of assessment requires detailed evaluation of the inter-specific differences in response and a knowledge of the likely outcome of competitive interactions. This table illustrates the futility of attempting to assess climate change impacts on a sectoral basis, the possible consequences of a rise in sea level cannot beassessed in isolation from other sources of change, since the limiting environmental factor to mangrove productivity and ecosystem stability in any one location may be completely unrelated to sea level.

To cope with the level of complexity involved in evaluating ecosystem responses to climate change and sea level rise non-linear dynamic models are required. However it could be argued that our present database is inadequate for the construction and testing of such models and that at the present time given the inadequacy of the biological database combined with the uncertainties of climate scenarios a traditional approach based on the identification of key environmental variables and ecological limiting factors is adequate for providing initial insights into ecosystem responses.

Table 6. Initial tabulation of some of the potential responses of mangrove species and ecosystems to changes in environmental factors as a consequence of climate change and sea level rise.

Environmental Change	Environmental consequences	Individual/population response	Ecosystem response
Temperature increase	Increased potential evapo-transpiration	Increased water stress Reduced productivity Reduced litter fall	Reduced vertical accretion rate
High latitudes		Increased production Increased litter fall	Extension of range Increased species diversity
Tropics/subtropics		Changes to growth & productivity Changes to competitive ability	Changed species composition
Precipitation change	Changed water balance Changed water table Changed sediment flux Changed nutrient flux	Altered growth & survival	Changed species composition Changed accretion rates Changed zonation
Precipitation increase		Decreased water stress Increased growth	Regression of landward margin
Precipitation decrease		Increased water stress Decreased growth	Reduced progression Inland extension
CO_2 increase		Increased growth Increased litter fall	Increased rate of vertical accretion
Sea level rise	Changed salinity gradients Inundation	Altered succession Enhanced mortality Reduced seedling establishment	Changed zonation Frontal regression Landward extension
Increased storm frequency & intensity	Increased erosion	Increased windthrow and other damage	Changed species composition

5. Relative Vulnerability of Classes of Mangrove Systems

On the basis of the above discussion it might be concluded that the class of mangrove formation occurring in undisturbed environments which is most vulnerable to projected climate change and sea level rise is that found on coral coasts and low islands. Mangrove formations found in coastal lagoonal areas and composite alluvial plains behind coastal beach ridges are probably the two next most vulnerable systems followed by mangroves in tidal plains and mangroves in alluvial plains. Possibly the least sensitive to projected changes are the mangrove systems presently found on drowned bedrock coasts. In proposing this relative vulnerability ranking for the six recognised classes of mangrove systems it is not suggested that each individual area will conform exactly to this pattern and qualifiers can be added to provide a vulnerability ranking such as that proposed in Table 7.

In examining the proposed relative vulnerability ranking outlined in Table 7 it should be further noted that no account is taken of a number of other factors which will alter the relative vulnerability of mangrove ecosystems at a particular site. Geological and geomorphological factors such as crustal downwarping, sediment compaction and the source of sediments need to be added to this ranking. A mangrove ecosystem which is located in an area of crustal downwarping such as that of the Gulf Province is clearly already subjected to relative rise in sea level. The greater the rate of subsidence then the greater the rate of relative sea level rise and hence the higher the relative vulnerability. Similarly where mangroves are located in a sedimentary basin or on alluvial plains the rate of soil erosion in the catchment determines the rate of allochthonous sediment inputs to the mangrove system. Low erosion rates mean low sediment inputs and hence greater vulnerability to sea level rise than in areas with high erosion rates. Comparatively mangrove areas which depend on sediments derived via long-shore drift are more vulnerable to sea level rise than those dependent on erosion products from the hinterland since a greater number of intervening factors controlling sediment flux may be adversely affected by climate change and sea level rise.

Table 7. Suggested vulnerability ranking of major classes and sub-classes of mangrove systems to potential sea level rise.

CLASS OF SYSTEM	SUB-CLASS	Relative Vulnerability within class	Overall relative vulnerability
Coral Coasts	Cays and motu	High	Extremely high
	Raised coral	Medium	Very high
	High islands	Low	High
Barriers & Lagoons	Unconsolidated barrier	High	High
	Bedrock barrier	Low	Medium to high
Composite alluvial plains and barriers	High sediment	Low	Medium
	Medium sediment	Medium	Medium to high
	Low sediment	High	High
Tidal plains	High sediment	Low	Medium to low
	Medium sediment	Medium	Medium
	Low sediment	High	Medium to high
Alluvial plains	High sediment	Low	Low
	Medium sediment	Medium	Medium to low
	Low sediment	High	Medium
Drowned bedrock	High slope	High	Low
	Low slope	Low	Very low

6. Discussion

Any consideration of the potential impacts of future climate change and sea level rise on a single ecosystem would be pointless if it were conducted in isolation from a consideration of the other factors currently affecting the status of the ecosystem.

Tropical coastlines world-wide are currently subject to increasing stress as a consequence of anthropogenic activities in combination with increasing human population density (Pernetta & Elder, 1992). It has been estimated that around two thirds of the worlds population currently lives in close proximity to the coastline and 65% of cities with populations in excess of 2.5 million are coastal. As a consequence coastal wetlands, including mangroves are coming under increasing pressure from urbanisation, coastal agriculture (particularly rice production) and mariculture (penaeid prawns). Even where large scale conversion of mangroves is not occurring increasing levels of unsustainable resource extraction including felling for fuelwood and charcoal is severely depleting these ecosystems. In combination with other sources of stress such as increasing levels of pollution from both domestic and industrial sources mangroves even where they are not being physically destroyed are becoming increasingly degraded. Hutchings and Saenger (1987) in examining the global distribution of mangroves note that with the exception of Australia, the worlds remaining large mangrove areas are all found in developing countries. They cite the case of Puerto Rico as an example of the way in which the rate of mangrove destruction rapidly increases to the point of almost complete loss as pressures on the resource grew during the sixties and seventies. Hutchings and Saenger further note that Puerto Rico is by no means unique and that mangroves are also undergoing massive destruction in countries such as Indonesia, the Philippines, Gambia, Ecuador, and Benin.

One further source of stress on many mangrove systems, particularly those on alluvial plains is sediment starvation as a consequence of dam construction. In many developing countries extensive dam building for irrigation and hydro-electric power has altered both the hydrological regime of individual drainage basins and the sediment flux to coastal and near-shore ecosystems. The collapse of the Egyptian coastal fishery as a consequence of the construction of the Aswan High Dam is well documented. Less well documented are the ecosystem impacts of dam construction in major river systems such as the Indus (Milliman *et al.*, 1984) or on the Volta where construction of the Akosombo dam has had major impacts on the erosional regime of the Ghanaian coast (Ly, 1980). Davies (1979) noted that as a result of construction of the Kariba, Kafue and Cahora Bassa dams on the Zambesi/Kafues river system in eastern Central Africa the whole mangrove ecosystem demonstrated a dieback of between 1-400 m. Clearly, a careful retrospective analysis of past and present mangrove extent and zonation in such circumstances would do much to answer questions concerning the potential impacts of sea level rise.

Mangrove management plans are being increasingly seen as a mechanism to address these existing problems in countries as far apart as Asia and West Africa, however it is clear that although these management plans are being developed within the framework of local conditions they are often too sectoral in their approach and almost without exception fail to take account

of potential changes to the climate and hydrology of the management area which may occur as a consequence of climate change and sea level rise. If mangroves are to be managed on a sustainable basis then clearly a multi-disciplinary cross-sectoral approach to management must be developed based on a sound inter-disciplinary, scientific understanding of the way in which these ecosystems function.

7. Conclusions

It would appear obvious from the above discussion that in the case of mangroves the key factors or components of global change will differ according to the nature of the response which is being evaluated. Thus it would seem that:

- the dominant factors determining possible future latitudinal range extension are temperature related, moderated by coastal current regimes;.

- the factors determining changes to ecosystem stability, relate to the sediment budget and hydrology;

- changes to zonation within individual mangrove communities will be related to relative sea level rise;

- hydrological processes will determine both individual species and community responses.

It would seem likely therefore:

- that the distributional limits of mangroves will be extended on the eastern continental margins;

- that species diversity in mangrove communities will increase at higher latitudes;

- that latitudinal range extension will occur at the expense of saltmarsh communities;

- that mangrove communities presently receiving high allocthonous sediment inputs will survive the predicted rise in sea level;

- that mangrove communities with low external sediment inputs will be at risk from projected rises in sea level;

- that the resilience of the low diversity Caribbean mangrove community in the face of global change is unlikely to be as high as that of the more diverse Indo-west Pacific mangrove communities;

- that the relative vulnerability of different classes of mangrove systems could be easily assessed using agreed systems for classification.

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