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Climate change impacts on, and vulnerability and adaptation of mangrove ecosystems

Joanna C. Ellison
School of Geography and Environmental Studies,
University of Tasmania,
Locked Bag 1376, Launceston,
Tasmania 7250, Australia.
Email: Joanna.Ellison@utas.edu.au

Mangroves are invaluable resources in the ASEAN region, providing coastal protection, wood, and fishery resources. While the region supports the world's highest diversity of mangroves, many countries have lost 50% of mangroves in the last 20 years, to conversion and degradation. Mangrove ecosystems are also sensitive to climate change impacts, particularly sea-level rise. Sea level rise of 1.5-9.7 mm a^{-1} is projected by 2099, and mangrove accretion rates are usually less than this, resulting in dieback at the seaward edge, and inland recruitment. Rise in temperature and the effects of increased CO_2 levels should increase mangrove productivity, and continue expansion of mangrove species ranges into higher latitudes. UNEP/ GEF/ WWF has recently developed protocols for mangrove vulnerability assessments, combining mapping and micro-elevation determination, long term relative sea-level trends, monitoring of mangrove structure, productivity, condition and human interaction. Climate change adaptation strategies developed include reduction of stressors, strategic protected areas designation, rehabilitation of degraded areas, as well as collaboration with local communities to improve resource use efficiency.

Keywords

Mangrove, climate change, vulnerability assessment, adaptation, rehabilitation, monitoring

Introduction

Mangrove forests occur most extensively on low energy, sedimentary shorelines of the tropics, in inter-tidal situations such as deltas and estuaries. They have special adaptations for a salty environment such as aerial roots, which makes them unique from other trees.

Mangroves play an integral role in coastal ecosystems, at the interface between terrestrial, freshwater and marine systems. They afford protection to both terrestrial and estuarine systems from high energy marine processes, preventing erosion and providing coastal communities substantial protection from tropical cyclonic storms. They also act to filter runoff water, and so protect offshore seagrass beds and coral reefs from deposition of suspended matter discharged by rivers. For centuries, mangroves have provided a wide range of products for coastal communities, such as timber and fuelwood, and bioactive compounds for tanning and medicinal purposes (Ewel et al., [1]).

Probably the most important value of mangroves to people is the ecosystem's support of ecologically and economically important fish species (Robertson and Duke, [2], Baran and Hambrey [3], Mumby et al. [4], Chitaro et al. [5]). The habitat is known to act as nursery sites for many commercial fish and crustacean species that are later available offshore. Many studies have shown that mangroves harbour high densities of juvenile reef fish (Ley and McIvor, [6]). Mumby et al. [4] showed that mangroves provide an intermediate nursery stage between seagrass beds and patch reefs, through alleviation of predatory loss, and increasing the survival of young fish. Mangroves enhance the adult fish biomass through provision of refuge from predators, and the provision of plentiful food that increases the survivorship of juveniles. This is attributed to the high abundance of food and shelter to be found in mangroves, and reduced predation. Mangroves therefore strongly influence the community structure of fish in offshore waters. In addition, the biomass of severally commercially important species is more than doubled when the adult habitat is connected to mangroves (Mumby et al., [4]).

Present status

Despite these values, many mangrove systems have been degraded and destroyed throughout their ranges (Valiela et al., [7]; FAO, [8]), and as a result, many coastal towns and communities are losing resources on which they depend. Mangrove area worldwide has fallen from estimated 19.8 million hectares in 1980, to below 15 million hectares by the end of 2000 (FAO, [8]). These rates of loss are equivalent to the rates of loss of tropical rainforest, but generally receive far less attention (FAO, [8]).

The mangrove deforestation was 1.7% a year from 1980 to 1990 and 1.0% a year from 1990 to 2000 (FAO, 2003), but more recent estimates are of losses as high as 2-8% per year (Miththapala, [9]). Some countries do not have multi-year data available as yet for mangrove area so a rate of loss is not quantifiable (Valiela et al., [7]). Key impacts include overharvest for timber, clearing of mangroves for agriculture and aquaculture, coastal development, and pollution, which are leading to habitat degradation and deteriorating water quality.

Climate change will compound the effects of many of these threats, particularly as mangrove forests are known to be one of the most vulnerable ecosystems to be strongly affected by the rise in sea level caused by climate change (Ellison, [10]). Loss of these coastal buffering systems due to climate change and other causes eliminates any protection they might afford, and may have significant environmental, social, and economic consequences for coastal communities.

ASEAN Mangroves

South East Asian countries have mangrove forests of among the highest biodiversity in the world, with a total area of 60.9 x 10^2 km^2 (Table 1). Globally, mangrove biodiversity is highest in the Indo-Malay Philippine Archipelago (Figure 1), with between 36 and 47 of the 70 known mangrove species occurring in this region (Duke et al., [11], Polidero et al., [12]). Southern New Guinea (including West Papua) has the greatest diversity of mangroves in the world, and is the location of the centre of the Indo-Malayan mangrove centre of diversity (Duke, et al., [11]).

The region however has among the highest rates of mangrove loss in the world, losing 628 km^2 per year in the last couple of decades. As the area data used in these assessments precedes the 2004 Asian Tsunami, the cause has been due to human impacts (Valiela et al. [7], Manhas et al., [13], Duke et al., [14]).

The greatest cause of this loss in the ASEAN region has been conversion of mangrove intertidal areas to mariculture ponds (such as shrimps) (Valiela et al. [7]; Armitage, [15]). Pond culture is responsible for 50% of mangrove loss in the Philippines, and 50-80% in Southeast Asia (Wolanski et al., [16]). There are further indirect damage from this to coastal values, such as discharge of nutrient rich waters which cause eutrophication, associated depletion of natural stocks of fish and crustaceans, and accumulation of toxins at the facility that cause it to be unusable after a few years, leading to faciilty abandonment becomes degraded (Wolanski et al., [16]), and conversion elsewhere of further mangrove forest. As well as direct clearing of mangroves for coastal development, aquaculture, or resource use, heavily populated coastal zones have led to further widespread degradation. Over-exploitation for fuelwood and timber production has degraded 26% of mangrove forests (Valiela et al., [7]).

Of special concern in the ASEAN regions are the two species of mangrove recently listed as Critically Endangered, the highest probability of extinction measured by the IUCN Red List (Polidoro et al., [12]). The rare *Sonneratia griffithii* is distributed in parts of India and southeast Asia, where a combined 80% loss of all mangrove area has occurred within its patchy range over the past 60 years (Ong [17]). It is reported to be locally extinct in a number of areas within its range, primarily due to the clearing of mangrove areas for rice farming, shrimp aquaculture, and coastal development. *Bruguiera hainesii* is also a very rare species recently listed as Critically Endangered, and is only known from a few fragmented locations in Indonesia, Malaysia, Thailand, Myanmar (Kress et al. [18]), *Camptostemon philippinense* has been recently listed as Endangered, and has an estimated 1200 or fewer individuals remaining due to the extensive removal of mangrove areas for both aquaculture and fuelwood within its range (Polidoro et al., [12]). The Endangered *Heritiera globosa* has the most restricted distribution in this region (extent of occurrence <5,000 km^2) as it is only known from western Borneo in Indonesia, where its patchily distributed, primarily riverine habitat has been extensively cleared by logging activities and for the creation of timber and oil palm plantations (Polidoro et al., [12]).

Mangrove forests in the region, despite their values to coastal communities, have suffered heavily from human impacts. This has caused sever reduction in their ranges, and recently it is becoming apparent that their biodiversity is now at risk. They are also sensitive to impacts from climate change, particularly sea-level rise.

Mangrove change impacts on mangroves

There are many reviews that have well demonstrated that mangroves are affected by climate change, these are summarised in Table 2.

The response of mangroves to such impacts tends to be gradual and, particularly in undisturbed systems, is manifested typically as a change in their extent, structure and species composition and hence their species zonation. As mangroves are sensitive to even minor transitions in coastal conditions such as altered drainage patterns, saltwater intrusion, accretion or erosion of sediment (Ellison, [19]) changes in the zonation of these ecosystems are often indicative of broader scale changes and associated impacts in coastal regions (Ellison et al., [20]; Ellison, [19]).

The fate of mangrove habitats to climate change globally will depend on a number of factors, including current tidal range, sedimentology, salinity regime, community composition and shore profile. Low relief shorelines and low islands will show more change. Sea-level rise will have more impact on intertidal systems in micro-tidal areas, than macro-tidal areas, and in areas that already suffer from relative sea-level rise due to deltaic subsidence.

Temperature rise

Mangrove distributions are limited by temperature in subtropical latitudes, at the 16℃ isotherm for air temperature of the coldest month. However studies of mangrove survival under high temperature stress from thermally polluted areas such as power station effluents (Canoy, [21]; Banus, [22]), show limits far higher than the current climate change projections, unlike the case for coral reefs.

Plant and soil biochemical processes are affected by increases in water and air temperatures, both photosynthetic carbon gain and respiration being highly sensitive to temperature (Lovelock and Ellison, [23]). Photosynthesis in mangroves in much of the tropics is limited by high midday leaf temperatures causing high vapour pressure deficits between leaves and air, resulting in stomatal closure (Clough and Sim [24], Cheeseman [25], Cheeseman et al. [26]). However, photosynthesis is limited by low temperature at southern latitudes (Steinke and Naidoo [27]). Increases in temperature where combined with declines in humidity and rainfall could reduce productivity in lower latitudes by accentuating midday depressions in photosynthesis (Lovelock and Ellison, [23]). Conversely, increasing primary production would be expected at higher latitudes through increases in the length of the growing season. The effects of temperature on primary production may be strongly influenced by other climate change and environmental factors that influence stomatal aperture and photosynthetic rates (eg rainfall, humidity and nutrient availability).

Increased atmospheric CO_2

As well as its enhanced greenhouse effects, increased CO_2 directly affects plant growth and development. CO_2 is the substrate for photosynthesis and influences respiration. CO_2 concentrations in the atmosphere have increased from 316 ppm in 1959 to 388 ppm today (Tans, [28]) and are predicted to grow 40-110% by 2030 (IPCC, [29]), with potentially profound effects on physiological and ecological processes in all plant communities. Because of the sensitivity of these key physiological processes to elevated CO_2, primary production in plant communities are highly sensitive to atmospheric CO_2 concentrations (Drake et al. [30]).

There are limted studies of the impacts of elevated CO_2 on mangroves. In other higher plants, photosynthesis and growth is often enhanced at doubled atmospheric CO_2 concentrations, however the level of enhancement is dependent on other interacting environmental factors (Drake et al. 1997). Farnsworth et al. [32] grew seedlings of *Rhizophora mangle* in doubled levels of CO_2 and demonstrated significantly increased biomass, total stem length, branching activity and total leaf area compared with seedlings grown in normal levels of CO_2. Ball et al., [33] found that the benefits of increased CO_2 may only occur where mangroves are not limited by high salinity or humidity. This may suggest that upstream productivity and expansion of mangroves into fresh and brackish wetlands could occur at an accelerating pace.

The available data suggests that under future elevated CO_2 primary production is likely to be enhanced, although not uniformly over the range of mangrove environments (Lovelock and Ellison, [23]). Increases in CO_2 concentrations may partially reduce the negative effects of reduced humidity and rainfall expected where temperatures increase in lower latitudes. Increasing levels of CO_2 may also change patterns of species dominance and accelerate mangrove encroachment into adjacent brackish and freshwater wetlands.

Combined with higher atmospheric CO_2 levels, climate warming can be expected to increase mangrove productivity, characterized by increased growth and litter production at all locations. Mangroves in higher latitudes are likely to become taller and more productive. With climate warming there may be change in phenological patterns (such as the timing of flowering and fruiting).

UV changes

Ultraviolet-B (UV-B) radiation is damaging to proteins and nucleotides and thus enhanced levels can lead to damage in plant tissues. Surface UV-B radiation has increased by approximately 6% in the Southern Hemisphere mid-latitudes and 130% in the Antarctica, relative to 1970's values (Madronich et al., [34]).

Mangroves have a suite of pigments that absorb UV-B radiation within their leaves likely due to their evolution in tropical latitudes where UV-B radiation levels are high (Lovelock et al. [35]; Lovelock and Ellison, [23]). Impacts of enhanced UV-B radiation are most likely to more affect plants in temperate regions. Anticipated effects include small reductions in photosynthetic rates and altered morphology (Caldwell et al. [36]). Although, UV-B radiation is predicted to have a large effect on subtidal primary producers, effect on intertidal plants are not expected to be large (Day and Neale [37]).

Precipitation changes

Mangrove distributions generally demonstrate that taller, more productive and more diverse forests grow on coasts with higher rainfall, while on drier coastlines mangroves are stunted, of narrower margins, and interrupted by salt flats.

The reasons for these patterns relate to salt stress. Under humid conditions, mangrove soils are almost continuously leached by heavy rains and fresh water is available from river discharge and groundwater outflow, which provides nutrients. Under arid conditions, evaporation from the intertidal mangroves at low tide leads to high concentrations of salt, in some cases resulting in unvegetated hypersaline flats around high tide level.

Increase in salinity in mangroves leading to salt stress can result from a number of factors in addition to reduced rainfall, such as groundwater depletion owing to reduced freshwater flux, groundwater extraction, and sea-level rise. Two major physiological adaptations enable mangrove survival in saline ocean water (Scholander, *et al.*, [38]), salt exclusion in species of *Rhizophora* and *Laguncularia*, and salt excretion in species of *Aegialitis* and

Aegiceras. Salt excluders also cease or diminish transpiration and photosynthesis when exposed to saline water. Salt secretors can continue photosynthesis utilizing ocean water in transpiration, owing to salt glands in the leaves.

Stern and Voight [39] grew 200 seedlings of *Rhizophora mangle* under different salinities, finding that seedling survival and growth increase by dry weight and seedling height were all inversely related to salt concentrations of the growing solutions. Ball and Farquhar [40] studied gas exchange characteristics in *Aegiceras corniculatum* and *Avicennia marina* under different salinity and humidity conditions. They showed decreased photosynthetic capacity with increase of salinity, with *Aegiceras* being the more sensitive. Ball and Farquhar [41] studied the gas exchange characteristics of *Avicennia marina* with increasing salinity, finding that CO_2 assimilation rate, stomatal conductance, intercellular CO_2 concentration and evaporation rate all decreased. Increased salinity has the effect of decreasing net primary productivity and results in reduced growth, with a differential effect on species. Reduced precipitation and a rise in sea-levels could result in stress to and changing competition between mangrove species.

Increased rainfall should result in reduced salinity and exposure to sulphate, and an increase in delivery of terrigenous nutrients (Snedaker, [42]). The extent of mangrove areas can be expected to increase particularly on leeward shorelines, with colonization of previously unvegetated areas of the landward fringe, and the diversity of mangrove zones and growth rates should increase. Decreased rainfall and increased evaporation would reduce the extent of mangrove areas, particularly with loss of the landward zone to unvegetated hypersaline flats.

These responses of mangroves to changes in precipitation will occur in combination with response to climate warming, and increased CO_2. The net response of mangroves at each location will also be combined with local factors and direct human impacts. The more significant climate change impact to mangroves what will have effect in combination with these, is due to rising sea-level.

Sea level rise impacts

Mangroves occur between mean sea levels and the high tide elevations, making them particularly sensitive to sea level rise and other factors that influence hydrology of the intertidal zone. Within this intertidal habitat of mangroves, species have different preferences for elevation, salinity and frequency of inundation, resulting in these species zones. Figure 2 shows the simplified mangrove zonation typical of the ASEAN region, with different species each favouring an elevation from mean sea-level up to high tide levels, where the mangroves change to landward communities.

Demonstrating this sea-level control of mangrove distributions, in extensive estuarine mangroves of SW Papua in Indonesia, elevations of mangrove zones (Figure 2) were accurately surveyed to show consistent zone elevations across a 1.9 m range within the mesotidal intertidal range of 3.5 m (Table 3) (Ellison, [43]). This sea-level control of mangrove locations is supported from other studies (Wolanski, et al., [44]; Ellison, [45]).

Geomorphological setting and tidal regimes of mangrove ecosystems and associated wetlands will strongly influence responses to sea level rise (Ellison, [19]). Tidal ranges are also anticipated to have a large impact on wetland responses to sea level rise, with greater exposure expected in areas with smaller tidal ranges compared to those with larger tidal ranges

Mangroves exist in active coastal settings, influenced by tidal movements, wave action, catchment runoff including floods and storm action. These are all direct influences on the sediment balance of the mangrove area, as well as indirect influences such as sediment supply either upstream, along shore or offshore. This sediment budget is summarised in Figure 3. The sediment budget is a balance of volumes of sediment entering or leaving the mangrove environment, influencing whether the environment is erosional or accretionary of a number of timescales.

Using a surface elevation table (Cahoon et al., [46]) in combination with a marker horizon enabled accretion to be distinguished from both shallow subsidence and elevation change. Across a variation of sites, Cahoon et al. [47] found that vertical accretion averaged 5 mm a^{-1}, elevation change 1 mm a^{-1}, and shallow subsidence 4 mm a^{-1}. These results over the last few years correspond well with radiocarbon dated long-term net rates of sediment accretion in mangroves (Ellison and Stoddart, [48]; Ellison, [43]).

In conditions where relative sea-level rise exceeds sediment accretion rates, mangroves die back from the seaward edge and retreat landward. This is demonstrated from the extensive coastal swamps of SW Papua (Ellison, [43]). Figure 4 is a pollen stratigraphic diagram typical of the whole coastline, showing a landward *Bruguiera* zone present at the core site for most of the Holocene, replaced around 3000 years ago by a more seaward *Rhizophora* zone. Net sediment accretion rates since that time were 0.5-0.6 mm a^{-1}, while the rate of sea-level rise was slightly more rapid at 0.67 mm a^{-1}, resulting in gradual landward migration.

Similar palaeoenvironmental records of mangroves from a number of locations with all shown sensitivity to sea-level rise, including dieback and massive mortality events (Ellison, [10, 43]). Sediment supply determines mangrove ability to keep up with sea-level rise. Mangroves of low relief islands in carbonate settings that lack rivers are likely to be the most sensitive to sea-level rise, owing to their sediment-deficit environments. However, as demonstrated from southern New Guinea, continental mangroves will also demonstrate significant mortality and attempt relocation inland.

The IPCC 4th Assessment projected rates of global sea level rise of 0.18-0.59 m by 2099 (1.5-9.7 mm a^{-1}) (IPCC, [29]). Inter-tidal mangroves are extensively developed on sedimentary shorelines, where accretion determines their ability to keep up with sea-level rise. These rates mostly exceed mangrove accretion rates (Cahoon et al., [47]).

In conditions of sedimentation surplus, mangroves colonise seaward either into bays especially offshore of river mouths or over reef flats. Panapitukkul et al. [49] demonstrated mangrove progradation of c. 38 m a^{-1} at Pak Phanang Bay in SE Thailand with high rates of river delivery of sediment. Such mangrove areas will be more resilient during rising sea-level. Mangroves have a unique feedback to climate change impacts in that they are able to promote sedimentation, and so protect the coastline from inundation owing their ability to foster high rates of sediment accretion. Other types of forest cover are unable to do this, mainly because they lack the sediment supply provided by tidal waters in estuarine situations.

Storm and wave impacts

Climate change projections include an intensification of tropical and extra-tropical cyclones, combined with larger extreme waves and storm surges (Nicholls et al., [50]). Mangroves have an important role in stabilising coasts during storm and tsunami events, both by frictional reduction of energy of waves, and promoting sedimentary resilience to erosion through the root mat (Massell et al. [51], Mazda et al. [52], Dahdouh-Guebas et al. [53], Danielsen et al. [54]; Katharesan and Rajendran, [55]; Vermaat and Thampanya, [56]*)*. Storm impacts geomorphologically can deposit marine sediments into mangrove seaward margins to either cause mortality or build shore parallel sand ridges or chenier ridges. Damage in mangroves following cyclones is usually a narrow zone of coastal wave damage, and complete defoliation over the narrow area of cyclone paths.

The dense foliage of mangroves combined with friction effects of aerial roots provides some facility in reducing wave power, including reducing damage from extreme events such as tsunami waves (Mazda et al., [56]). At high tide in a *Rhizophora* forest, there is a 50% decline in wave energy within 150 m of the seaward edge (Brinkman et al., [57]). The degree of protection obviously depends on the size of the waves, and the maturity and density of the forest (Yanagisawa et al., [58]), but with a tsunami wave of over 6 m mangroves are mostly destroyed.

There is a feedback between mangrove loss due to direct human clearance and climate change (Duke et al., [11]). Mangroves are a significant carbon store as a result of their extraordinarily high rates of primary productivity, hence clearance destroys that mechanism of CO2 reduction. Mangroves have furthermore been shown to promote coastal stability in conditions of erosion and high human impact also in the ASEAN region (Mazda et al., [52]; Thampanya et al. [59]).

Vulnerability assessments

Current knowledge therefore indicates that climate change effects on mangroves are significant, may already be occurring, and will continue to occur even after atmospheric CO_2 emissions are decreased during the long period of time to stabilization. Management of mangroves requires that we develop adaptive resource management strategies.

Vulnerability to climate change and adaptive capacity have recently emerged as useful terms for analysing coupled human-environment interactions (Adger et al. [60]). Focus in existing work has been more on the human or economic aspects of vulnerability than that of ecosystems, and adaptation has been more in human systems and management. Vulnerability is the susceptibility of exposure to harmful stresses, and the ability to respond to those stresses (Adger et al., [60]; Mertz et al., [61]).

Resilience is the ability to continue to function in the face of change, while resistance is the ability to absorb change and continue to function. Hence adaptation includes actions to reduce vulnerability or enhance resilience (Adger et al., [60]). Vulnerability to climate change in resource-dependent livelihood groups is increased if their natural resource base is severely stressed or degraded by overuse, or if their management systems are ineffective (Adger et al. [60]). This is the case for many mangrove areas of the tropics, where communities are largely dependent on mangrove resources such as fish, crustaceans and fuelwood. Hence a key adaptation response is improved management, education and awareness building, and community involvement in management.

There has been little development of methodologies for vulnerability assessments and adaptation strategies that are specifically useful in mangroves, or even in associated systems. Rather, most climate change vulnerability assessments have focused on particular human sectors or ecosystem types that are affected only by climate change, not in conjunction with sea-level rise.

While the condition of mangrove biodiversity is already degraded, climate change is anticipated to make conditions worse still, adding a level of urgency to the need to take action to better protect these ecosystems. Mangrove communities are spread across the world's tropical coastline, generally in areas with limited funds for conservation or research, and little technical capacity for assessing biodiversity threats and developing conservation strategies.

While there have to date been no climate change vulnerability assessments focussed on sustaining the biodiversity of mangroves, there are several projects both past and current that focus on conservation and sustainable management of mangroves. Much of this work has been in the ASEAN region or adjacent, initially owing to the use of mangroves as forestry resources in countries such as Malaysia and Thailand. Several local projects have addressed mangrove restoration and climate change (e.g. the Vietnam Red Cross Society's Mangrove Reforestation Project).

Several studies have underlined the importance of addressing climate change threats to mangroves (e.g. Ellison, [10]; Lovelock and Ellison, [23]). McLeod and Salm [62] laid out ten guidelines for increasing resilience of mangroves to climate change, but the adaptation and management implications of their review needs to be further tested.

Climate change is an immediate, global threat; even the best-case scenarios indicate that it will continue to be a major threat for centuries to come. It is therefore essential that we develop ways to increase the resistance and resilience of mangroves to climate change, since we will not be able to completely prevent such change from occurring. Because there is neither the time nor the money for a site-by-site approach to methods development, a generalizable methodology is needed for vulnerability assessment and creation of adaptation strategies that can be applied in multiple ecological and sociopolitical contexts.

With support from UNEP Global Environment Facility and in close collaboration with a range of stakeholders and local communities, WWF has been working in three target countries to build and strengthen the capacity of local managers to assess mangrove vulnerability to climate change impacts, and use results to develop appropriate adaptation.

The vulnerability assessment methodology is designed to understand what aspects of the system are already experiencing climate change impacts or what aspects are most vulnerable to future impacts given existing, non-climate stresses which could exacerbate problems cause by climate change or limit a system's ability to respond to environmental changes. Project activities are being implemented initially in three countries: Cameroon, Fiji, and Tanzania, as low-lying coastal areas, particularly those in tropical Africa and the South Pacific, are predicted to experience among the most dire consequences of global climate change (IPCC, [29]). Many of these areas are occupied by traditional cultures which are dependent on the natural resources provided by healthy coastal ecosystems.

Detailed site-based mangrove vulnerability assessments are being conducted in each country, which combine a range of approaches (Table 4). These include reconstruction of the site's relative sea-level history, as most developing country locations with mangroves lack long-term tide gauges.

Global sea-level rise projections need to be added to this background rate for determination of local future scenarios. Changes in mangrove extent as indicated by comparison of past and recent aerial images are verified by local community surveys through the WWF “Climate Witness” program. Permanent plots are a well established technique for long-term monitoring of mangroves, with which data collected can be compared, and provide a basis for monitoring beyond the timeframe of the current project. Mangrove condition surveys are being carried out in conjunction with local community participants, to provide information on human impact levels or indication of natural changes.

The VA process includes involvement of multiple stakeholder groups in each of three countries throughout the planning and execution stages of the project. This ensures national and local capacity-building in target countries, as well as on-the-ground projects demonstrating practical approaches to vulnerability assessment and adaptation. Adaptation measures target factors influencing the resistance and resilience of the mangrove ecosystem, in conjunction with the local communities who depend on the mangroves.

Adaptation

Adaptability refers to the degree to which adjustments can be made in practices, processes, community structures of systems to projected or actual changes of climate (Adger et al., [60]; Mertz et al., [61]). Adaptation can be spontaneous, or planned, and can be carried out in response to or in anticipation of changes in conditions. Adaptive capacity is the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities or to cope with the consequences

Results from the GEF/ UNEP/ WWF mangrove resilience project are being used to develop a range of develop appropriate adaptation strategies. These include the designation of strategic protected areas and improved management of sustainable use areas, rehabilitation of degraded areas, reforestation with “climate-smart” mangrove species, more integrated land-use and marine planning, as well as collaboration with local communities to improve resource use efficiency. Success depends on the involvement and commitment of communities affected by an adaptation strategy. Thus any plan must strengthen rather than weaken the livelihood security of these communities. Community stakeholders are involved in the planning, implementation, and evaluation stages of the project to ensure that their needs are met.

In the end, the long-term success of any project will hinge upon local capacity, on the existence of sufficient information and expertise to allow local stakeholders to continually adjust existing strategies and to develop new ones. This project addresses capacity building by engaging individuals and organizations that play key roles in disseminating information, including research and academic institutions and local opinion leaders.

Response measures to some degree differ between trial sites, because of varying ecological, economic, political, and cultural conditions. Management strategies responding to climate change are not dissimilar from traditional conservation methods; however more emphasis is placed upon increasing spatial and temporal scales, protection of key communities known to be resilient, managing specifically for increased disturbances, and maintaining flexibility given uncertainties and surprises surrounding what climate change will bring (Hansen, [63]).

A basic premise to increasing resilience to climate change is enhancing or protecting the system's natural ability to respond to stress and change (Adger et al., [60]; Mertz et al., [61]). Reduction of other stresses on mangroves increases ecosystem biomass and species diversity. Such adaption options include capacity building of local communities to better manage mangrove areas, community based monitoring of mangrove condition, and rehabilitation of degraded areas.

Local communities that utilize resources in the project sites are assisted to design a suite of response measures that will both enhance human livelihoods and reduce pressure to the coastal ecosystem. For example, one response measure includes enhancing the efficiency of use of mangrove wood with better cooking/ wood smoking technologies. Mangrove wood is used widely by local communities in some of the project areas for drying fish. Low-cost cook-stoves (Figure 5) have been developed and encouraged exist that use up to 75% less wood, substantially reduce cooking time and also fumes that cause health problems in humans.

Improving management and planning

Resilience building in response to climate change involves revision of the design and management of protected areas. Improved land/marine use planning is a key response measure to build resilience and resistance to climate change. For example, protected areas can be designed to better allow for species, population and ecosystem preservation in light of mounting climate change related pressures. This can include altering reserve design to include habitat refugia, adding robust corridors, linking reserves of different habitat types (such as marine and mangrove), or changing use allowances during periods of added stress.

WWF has been working with communities in Tikina Wai, Fiji since 2000, where 3 mangrove reserves are now established and managed by a marine resource committee with representatives from 6 villages. Village surveillance and monitoring enables feedback to the committee on any resource abuse or decline in fish or crab availability, and decisions are made on this basis.

Unfortunately, the areas where mangroves will seek habitat with sea-level rise are those areas most favored by human development, the coastal lowlands. They are converted to other uses: agriculture, roads or coastal settlements. Conservation of buffer zones behind mangroves to anticipate landward migration with sea-level rise will improve future resilience of mangroves in the region.

The largest threat to the resilience of intertidal wetlands with climate change is the presence of barriers that will prevent the landward migration of intertidal wetland communities (Lovelock and Ellison, [23]; Gilman et al., [64]). Barriers to landward migration of intertidal communities can be imposed by natural features e.g. steep slopes, but urban, agricultural and other human developments that build berms, bunds, seawalls and roads on coastal plains impose significant threats to resilience of mangroves, salt marsh and salt flats with sea level rise. Barriers also reduce connectivity between ecosystems and overall productivity.

Reducing threats to resilience requires determining areas for future mangrove migration, and adaptation or removal of barriers to migration. Areas of greatest concern are those that are highly developed or converted to other uses, and which also have a relatively low tidal range. Additionally, where sediment and freshwater inputs (rivers and groundwater) are reduced, barriers to landward migration will have a greater negative impact on these intertidal wetlands.

Mangrove rehabilitation

Rehabilitation of degraded mangrove systems will likely be one of the most effective strategies for building resilience, particularly where sections are degraded of an otherwise healthy system. Mangroves that are degraded are more likely to show impact from climate change effects than mangroves that are healthy (McKee, et al., [65]). Healthy mangroves cause sediment accretion and land building, while degradation of mangroves can cause coastal erosion.

There is a wealth of experience in mangrove restoration and replanting in many countries of the ASEAN region (Agaloos, [66]; Hong, [67]; Chan, [68]; De Leon and White, [69]; Biswas et al., [70]), that if supported can strongly increase regional adaptive capacity. The objectives of mangrove replanting earlier included timber production or silviculture (Malaysia, Bangladesh, and Pakistan); enhancement of coastal protection (Thailand), but more recently is mostly for the restoration of degraded areas.

Following coastal erosion in the Upper Gulf of Thailand, the Government of Thailand approved a national mangrove management plan in 1987, including funding of a mangrove rehabilitation project (Winterwerp et al., [71]). Beneficial effects identified included increase of sediment capture and sediment stabilisation, increase of habitat for species such as crabs and coastal fisheries, and increase of resting and feeding habitat for migrating and local birds.

In any rehabilitation project, it is necessary to engage the support of the local community or village that has traditional use of the mangrove area, and to engage the support of other interested stakeholders. At Yadfon in Thailand, a village community forest was established constituting a replanted mangrove area, with a committee of 10 to 20 people selected to guide its management (Quarto, [72]). This was part of a larger cooperative program to help fishing people sell their daily catch and purchase fishing equipment, recognising the knowledge of the local fishers and the restriction of lack of opportunities. Within two months of replanting mangroves, the villagers began noticing an increase in their near-shore fish catch, and appearance of species of fish that had previously been rare. Later, villagers were encouraged to use the by-products of the community forest without extensive harvesting of the trees. By products might include limited fuel-wood gathered from dead or fallen branches, and collection of fruit or leafy parts for food or medicinal uses. Fish and shell-fish that occur naturally in the prop roots of the mangroves were collected. As part of the community welfare system, more needy families in the community were prioritised in receiving permission from the committee to extract a limited amount of the forest resource to supplement their livings.

<u>Mangrove monitoring to assist adaptive management</u>

Responses of mangroves to climate change will include responses to climate warming, increased CO_2, changed precipitation and sea-level rise. The net response of mangroves at each location will also be combined with local factors and other impacts. Management of these changes will facilitated by monitoring and regional information sharing on mangrove changes and trends. The ASEAN region has already been progressive on development of techniques for mangrove monitoring, supporting the ASEAN-Australia initiatives that led to manuals such as English et al. (1997). Regional coordination of these efforts would assist mangrove adaptation.

Regional monitoring networks of mangrove species, condition and productivity allowing identification of change would assist informed management with respect to climate change effects on mangroves. The Ramsar Convention gives guidelines to define management objectives of which monitoring is part, the principal of which is to maintain ecological character or ecological integrity of the wetlands. Wetland inventory, assessment and monitoring are distinguished as:

- Wetland inventory is the collection of information to describe the ecological character of wetlands.
- Wetland assessment is the identification of threats to wetlands.
- Wetland monitoring is collection of specific information for management purposes in response to hypotheses derived from assessment activities.

Wetland monitoring programs need to be of long time duration to be useful to wetland management. In the case of sea-level rise and climate change impacts to mangroves, the later monitoring commences the poorer the baseline starting point will be in defining the ecosystem character before impacts commence (UNEP/ UNESCO, 1993; UNEP, 1994)

Table and Figure Captions

Table 1. Mangrove species and areas in ASEAN countries (sources: Spalding et al., [76]; Valiela et al., [7]; FAO, [8]).

Table 2. Predicted effects of climate change factors on mangroves and key references (adapted from Lovelock and Ellison, [23]).

Table 3. Elevations of mangrove zones in the Ajkwa/ Tipoeka mangrove estuaries, West Papua, Indonesia (adapted from Ellison, [43]).

Table 4. Components of site based mangrove vulnerability assessment, GEF UNEP WWF mangrove resilience and adaptation project.

Figure 1. Mangrove global distributions, and indicative graph of low latitude mangrove species diversity.

Figure 2. Typical mangrove zonation of the ASEAN region (adapted from Ellison, [19]).

Figure 3. Sediment budget of a mangrove swamp (adapted from Ellison, [19]).

Figure 4. Late Holocene vegetation changes in the Tipoeka Estuary, West Papua, Indonesia (adapted from Ellison, [43]).

Figure 5. Mangroves cut in Douala mangrove area, Cameroon, and wood-burning stove for fish smoking designed for reduced input of mangrove wood.

Table 1

ASEAN Country	**Mangrove species**	**Mangrove area km^2**	**Year of estimate**	**Mangrove area km^2**	**Year of estimate**
Brunei Darussalam	29	70	1983	171	1997
Cambodia	5			601	1994
Indonesia	45			45421	1980's
Laos	n/a	0	n/a	0	n/a

Malaysia	36	7300	1980	6424	1994
Myanmar	24	5171	1965	3786	1996
Philippines	30	4500	1920	1325	1990
Singapore	31	18	1983	6	1990
Thailand	36	3724	1961	1687	1993
Viet Nam	29	4000	1945	1520	1995
Total	51			**60,941**	

Table 2

Impact	Processes affected	Likely response	References
Rising sea level	-Forest cover -Productivity -Recruitment -Sedimentation	-Forest mortaility seaward -Migration landward, but dependent on sediment inputs and and human modifications	Ellison, [45], Ellison and Stoddart [48], Semeniuk [78], Cahoon et al. [47], Ellison, [43]
Extreme storms (or tsunamis)	-Forest productivity -Recruitment reduced -Erosion and subsidence	-Forests damaged or destroyed	Dahdouh-Guebas et al., [53], Alongi, [77] Yanagisawa et al., [58]
Increased waves and wind	-Sedimentation -Recruitment	-Changes in forest coverage, depending on whether coasts are accreting or eroding (interaction with sediment stabilization from seagrass loss)	Semeniuk [78]
Increased air and sea temperature	-Respiration -Photosynthesis -Productivity	-Reduced productivity at low latitudes and increased winter productivity at high latitudes	Clough and Sim [24], Cheeseman [25], Cheeseman et al. [26]
Enhanced CO_2	-Photosynthesis -Respiration -Biomass allocation -Productivity	-Increased productivity, subject to limiting factors of salinity, humidity, nutrients	Farnsworth et al. [32] Ball et al. [33]
UV-B radiation	-Morphology -Photosynthesis -Productivity	-Minor	Lovelock et al. [35], Day and Neale [37] Caldwell et al. [36]
Reduced rainfall	-Reduction in sediment inputs, -Reduced ground water -Salinization	-Relative subsidence -Mangrove migration landward -Reduced photosynthesis -Reduced productivity -Species turnover -Reduced diversity	Whelan et al. [79],
Reduced humidity	-Photosynthesis -Productivity	-Reduced productivity -Species turnover -Reduced diversity	Clough and Sim [24], Cheeseman [25], Ball et al. [33]
Enhanced rainfall	-Increased sedimentation -Enhanced groundwater -Less saline habitats -Productivity	-Maintenance of surface elevation -Increased diversity -Increased productivity -Increased recruitment	Whelan et al. [79], Lovelock and Ellison [23]

Table 3

Mangrove zone	**Elevation relative to MSL** (m) (error ±0.2)
Avicennia/ *Sonneratia*	-0.35 to +0.15
Rhizophora	+0.15 to +1.1
Bruguiera	+1.1 to +1.6
Mixed mangrove/ Freshwater forest	above +1.6

Table 4

VA component	**Approach**
Assessment of mangrove species zones, condition, productivity (litter), phenology, biomass	Transect-based permanent plots, and rapid condition assessment techniques
Analysis of recent changes (last few decades)	Air photograph and satellite image analysis by GIS
Elevations relative to sea level (topography) – within mangrove forest	Surveyors level and water level correlation
Elevations - above tidal	dGPS survey
Sedimentation rates under mangroves	Deeply inserted sedimentation stakes
Evaluation of site's past relative sea-level trends	Stratigraphy, ^{14}C dating and pollen analysis
Compilation of local community knowledge	Social science techniques
Local community and stakeholder involvement	Capacity building, workshops and consultation
Adjacent ecosystem monitoring	Coral reef and seagrass surveys
Other	Waterfowl monitoring

Figure 1

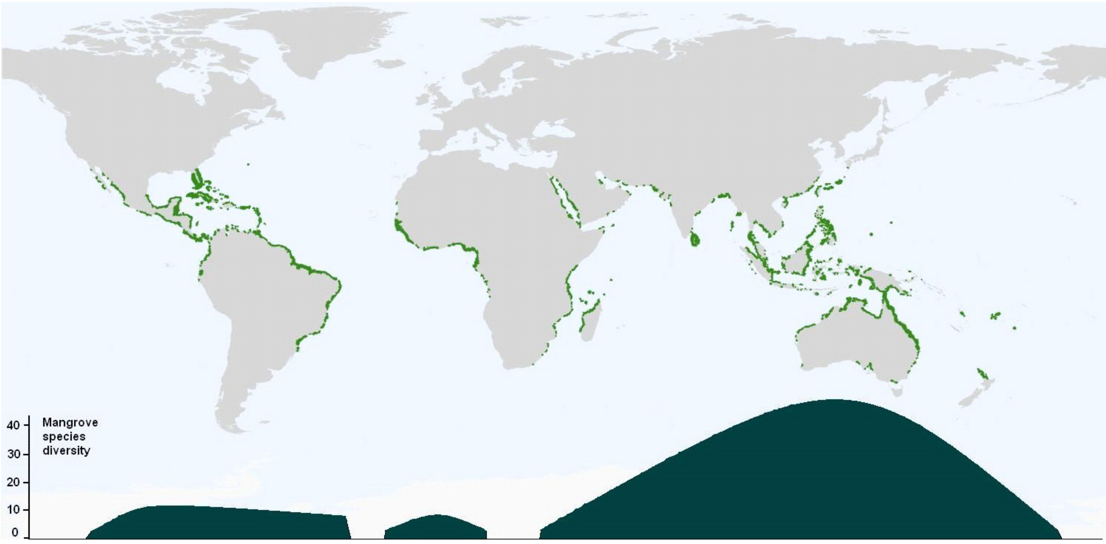

Figure 2

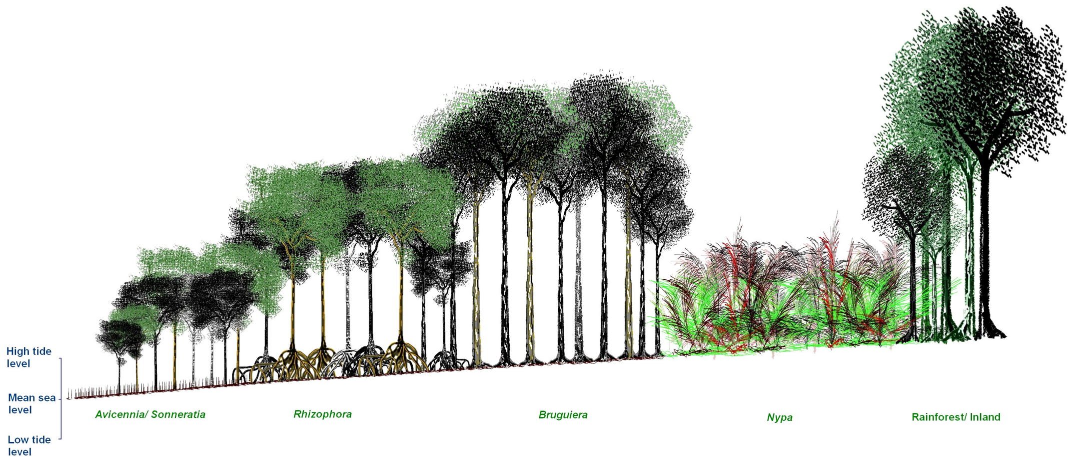

Figure 3

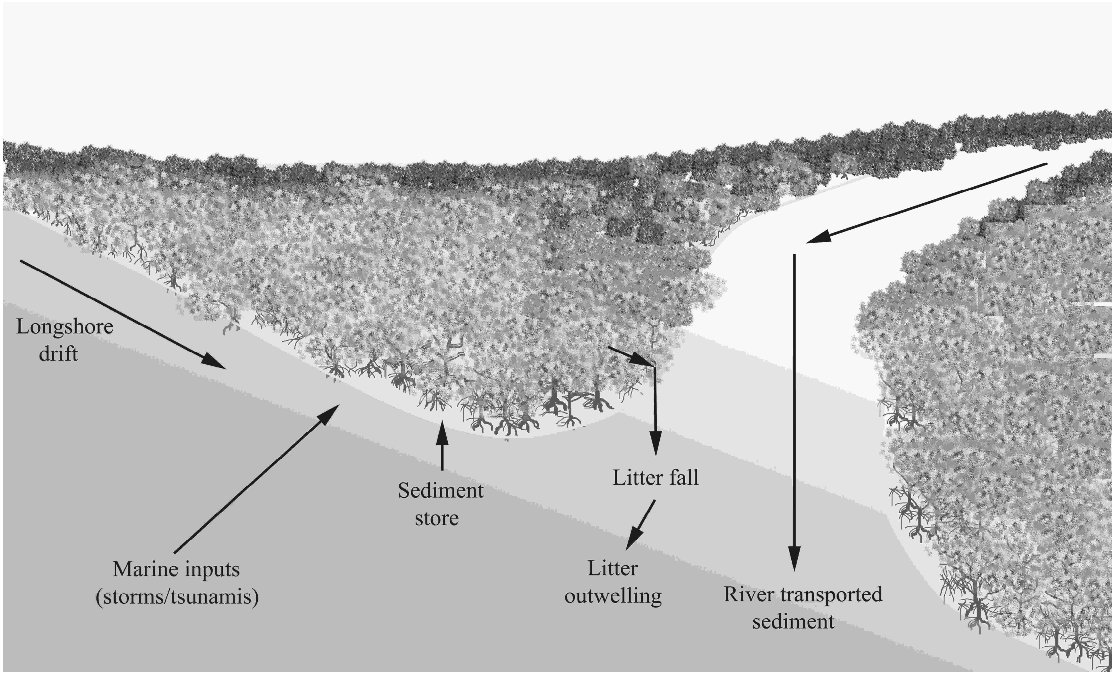

Figure 4

Figure 5

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