

Managing Mangroves for Resilience to Climate Change

Elizabeth McLeod and Rodney V. Salm



IUCN Resilience Science Group Working Paper Series - No 2

IUCN Global Marine Programme

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The IUCN Resilience Science Working Group

The IUCN Resilience Science Working Group on coral bleaching, resilience, and climate change was established in 2006 by the Global Marine Programme of IUCN, The World Conservation Union, on a 3-year grant from the John D. and Catherine T. MacArthur Foundation. The goal of the working group is to draw on leading practitioners in coral reef science and management to streamline the identification and testing of management interventions to mitigate the impacts of climate change on coral reefs. The working group will consult and engage with experts in three key areas: climate change and coral bleaching research to incorporate the latest knowledge; management to identify key needs and capabilities on the ground; and ecological resilience to promote and develop the framework provided by resilience theory as a bridge between bleaching research and management implementation.

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Front cover: Bruguiera flowers with fruit in Bali, Indonesia; Copyright: The Nature Conservancy

Back cover: Suaka Marga Satwa (Nature Reserve) at the mouth of the Wampu River - Langkat Regency, North Sumatra. Courtesy of Mangrove Action Project, Ben Brown

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Foreword

As anyone who has spent any amount of time in mangroves knows, these forests are some of the toughest places on earth. Subject to rapid daily, monthly, and annual variation in their physical environment, they have a remarkable ability to cope with extraordinary levels and types of stress.

The innate resilience of mangroves to cope with change is a requirement of their niche. Unfortunately, we have largely ignored that attribute in devising mangrove management programs or in regulating (and not regulating) their use and exploitation. Few management schemes adequately consider the effects of upstream development on sediment supply and even fewer consider the cumulative effects of mangrove clearing on connectivity over ecologically meaningful scales.

Perhaps even more telling is the lack of attention to the synergistic effects of human-induced and natural change. The damage caused by the tragic 2004 Asian tsunami was exacerbated by over clearing of mangroves and other coastal “bioshields”, inappropriate coastal development and inadequate information and preparedness. Imagine for a moment, just how devastating those same factors may be in a future world where sea levels may be higher, protective mangrove forests even less intact and coastal nations unsure about how changed meteorological and oceanic processes will combine.

If the millions of coastal residents who benefit from the services provided by mangroves are to survive and continue to enjoy the enormous benefits provided by healthy mangroves, then we need to quickly and proactively develop climate change-oriented mangrove management programs.

This publication is a most welcome reference for all stakeholders in mangroves, especially coastal communities, who should now ask decision-makers to apply resilience principles in all development and conservation programs.



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Table of Contents

1.	Introduction	6
2.	Overview of Mangrove Ecosystem	8
2.1	Definition.....	8
2.2	Global Distribution of Mangroves.....	8
2.3	Environmental Effects on Mangrove Growth.....	9
3.	Benefits of Mangroves	10
4.	Human Threats to Mangroves	11
5.	Potential Impacts of Climate Change	12
5.1	Effects of Changes in Temperature.....	12
5.2	Effects of Changes in CO ₂	13
5.3	Effects of Changes in Precipitation.....	13
5.4	Effects of Changes in Hurricanes and Storms.....	13
5.5	Effects of Changes in Sea Level.....	14
5.5.1	Mangrove Adaptations That Help Them Survive Sea-Level Rise.....	15
5.5.2	Environmental Factors That Affect Mangrove Response to Sea Level.....	16
5.5.3	Species Response to Sea-level Rise.....	16
6.	Assessing Mangrove Vulnerability to Sea-level Rise	17
7.	Ten Strategies Managers Can Apply to Promote Resilience	18
7.1	Spread Risk by Identifying and Protecting Representative Mangrove Habitats.....	19
7.2	Identify and Protect Refuges.....	19
7.3	Effective Management.....	21
7.4	Establish Greenbelts and Buffer Zones.....	22
7.5	Restore Degraded Critical Areas That Have High Survival Prospects.....	23
7.6	Maintain Connectivity Between Mangroves and Associated Systems.....	24
7.7	Establish Baseline Data and Monitoring Plan.....	25
7.8	Develop Adaptive Management Strategies.....	25
7.9	Develop Sustainable and Alternative Livelihoods for Mangrove Dependent Human Communities.....	25
7.10	Build Constituency and Partnerships at Local, Regional, and Global Scales.....	26
8.	Tools and Methods for Enhancing Mangrove Resilience	27
8.1	Low-tech Approaches to Measure Vulnerability to Sea-level Rise.....	27
8.2	Low-tech Approaches to Measure Changes in Salinity and Hydrology.....	28
8.3	Low-tech Approaches to Measure Changes in Elevation.....	28
8.4	High-tech Approaches to Determine Mangrove Response to Historical Sea-level Rise.....	30
8.5	High-tech Approaches to Predict Mangrove Response to Future Sea-level Rise.....	30
9.	A Framework for Action	32
10.	References	34
	Glossary.....	48
	Appendix 1 Detailed description of climate change impacts on mangroves.....	50
	Appendix 2 Summary of papers that address climate related impacts on mangroves.....	58
	Appendix 3 Mangrove mapping tools.....	59
	Appendix 4 Overview of publications addressing mangrove mapping methods and overall accuracy.....	61
	Appendix 5 Mangrove types.....	63

1. Introduction



Jaring Halus Village Mangrove Reserve in North Sumatra, Rhizophora mucronata planted nearly a year ago by the local fishing community of Jaring Halus. Copyright: Mangrove Action Project, Ben Brown

Global climate change is one of the greatest challenges that humans will face in this century. Although geological records show climatic changes throughout history, the present rate of global warming threatens the survival of entire ecosystems. Among the most at-risk ecosystems are mangroves, which are especially vulnerable to sea-level rise, but the good news is that not all coastlines with mangrove forests are projected to experience a rise in relative sea level. At sites that are projected to experience rising seas, mangrove ecosystems on low relief islands and those

deprived of sediment are especially vulnerable. In contrast, mangrove ecosystems with ample sediment supplies and/or room to move inland are likely to survive projected rates of sea-level rise. Mangrove species have demonstrated different tolerances to changes in sea level, salinity, and storms. By understanding which mangrove stands are able to survive sea-level rise and other changes, natural resource managers can identify and protect refuges that self-seed and act as sources for seeding of future mangrove communities.

This paper is an attempt to provide some considerations for conservation practitioners as they design conservation strategies for mangroves. These ideas build upon the concept of resilience that was developed by West and Salm (2003) to address coral bleaching. Resilience is the ability of a system to undergo, absorb, and respond to change and disturbance, while maintaining its functions (Carpenter et al. 2001). West and Salm (2003) outline several strategies to help managers identify: 1) reef areas that are naturally resistant to coral bleaching (i.e., resistant areas); and 2) reef areas where environmental conditions are likely to promote maximum recovery after bleaching mortality has occurred (i.e., resilient areas). West and Salm (2003) recommend that these key areas, where environmental conditions appear to boost resistance and resilience during and after large-scale bleaching events, be incorporated

into networks of marine protected areas. Although these principles were developed to address coral reefs and increases in sea temperature, similar principles of resilience can be applied to mangroves and sea-level rise.

Building resilience into mangrove conservation plans requires an understanding of how mangroves will respond to climate changes, what factors help them survive these changes, and, consequently, which mangroves are most likely to survive these changes. This paper provides an overview of mangrove ecosystems, discusses the benefits of mangroves to people, and the human and global threats that compromise mangrove ecosystems. This document describes the impacts of climate change on mangroves and outlines tools and strategies that enhance mangrove resilience.



Women collecting seafood by mangrove in Winneba, Ghana. Photo: Copyright IUCN, Michelle Laurie

2 Overview of Mangrove Ecosystem



Mangroves in Raja Ampat, Papua, Indonesia. Copyright: The Nature Conservancy

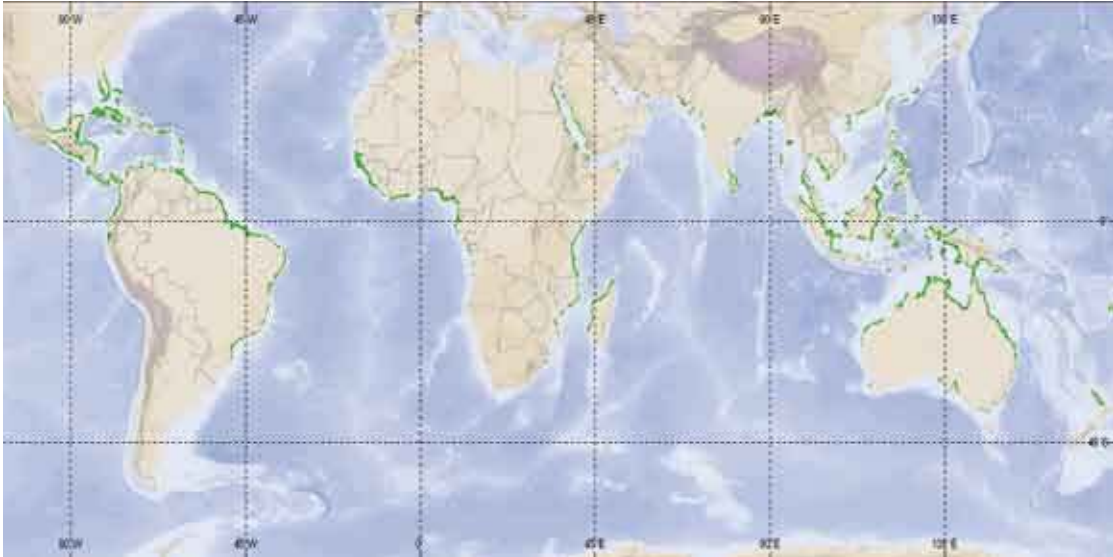
2.1 DEFINITION

Mangroves are a taxonomically diverse group of salt-tolerant, mainly arboreal, flowering plants that grow primarily in tropical and subtropical regions (Ellison and Stoddart 1991). A “mangrove” has been defined as a “tree, shrub, palm or ground fern, generally exceeding more than half a meter in height, and which normally grows above mean sea level in the intertidal zones of marine coastal environments, or estuarine margins” (Duke 1992). The term “mangrove” can refer to either the ecosystem or individual plants (Tomlinson 1986). Mangrove ecosystems have been called “mangals”

(Macnae 1968) to distinguish them from the individual plant species. The term “mangrove” as used in this report refers to the mangrove habitat type and not the constituent plant species.

2.2 GLOBAL DISTRIBUTION OF MANGROVES

Climatic factors such as temperature and moisture affect mangrove distribution (Duke 1992; Saenger and Snedaker 1993). In some areas, coastal processes such as tidal mixing and coastal currents may also influence mangrove distribution through affecting propagule dispersal (De Lange and De Lange 1994). Mangroves are distributed latitudinally within the tropics and subtropics, reaching



Global Distribution of Mangroves. Source: UNEP-WCMC 2006. Compiled by C. Ravilious, courtesy of UNEP-WCMC

their maximum development between 25°N and 25°S (Hensel et al. 2002). Temperature controls latitudinal distributions of mangrove; perennial mangroves generally cannot survive freezing temperatures (Hensel et al 2002). The richest mangrove communities occur in areas where the water temperature is greater than 24°C in the warmest month (Agrawala et al. 2003).

Estimates of mangrove area vary from several million hectares (ha) (UN Atlas of the Oceans) to 15 million ha worldwide (FAO and UNEP 1981). The most recent estimates suggest that mangroves presently occupy about 14,653,000 ha of tropical and subtropical coastline (Wilkie and Fortuna 2003).

2.3 ENVIRONMENTAL EFFECTS ON MANGROVE GROWTH

Mangrove species vary greatly regionally and with response to environmental factors. For example, in northeastern Queensland, the humid tropics with

high rainfall produce taller (up to 40 meters), highly productive, closed canopy mangrove forests; areas that are drier have increased water and salinity stress and produce shorter (1-5 meters), lower productivity, open canopy mangroves (State of the Marine Environment Report for Australia 2000). Generally, high latitude mangroves and mangroves found on arid coastlines have fewer species than tropical mangroves (UNEP 1994). The limiting factor for mangroves in higher latitudes is sea surface and/or atmospheric temperature (Saenger et al. 1977; Clüsner and Breckle 1987).

3 Benefits of Mangroves



Man throwing a cast net from a boat, Sulawesi, Indonesia. Copyright: Mangrove Action Project, Ben Brown

Mangroves have tremendous social and ecological value. The annual economic value of mangroves, estimated by the cost of the products and services they provide, has been estimated to be \$200,000 - \$900,000 per hectare (Wells et al. 2006). The mangrove ecosystem provides income from the collection of the mollusks, crustaceans, and fish that live there. Mangroves are harvested for fuelwood, charcoal, timber, and wood chips. Services include the role of mangroves as nurseries for economically important fisheries, especially for shrimp. Mangroves also provide habitats for a large number of molluscs, crustaceans, birds, insects, monkeys, and reptiles.

Other mangrove services include the filtering and trapping of pollutants and the stabilization of

coastal land by trapping sediment and protection against storm damage.



Cardinal fish among mangrove roots, Komodo, Indonesia. Copyright: The Nature Conservancy

4 Human Threats to Mangroves

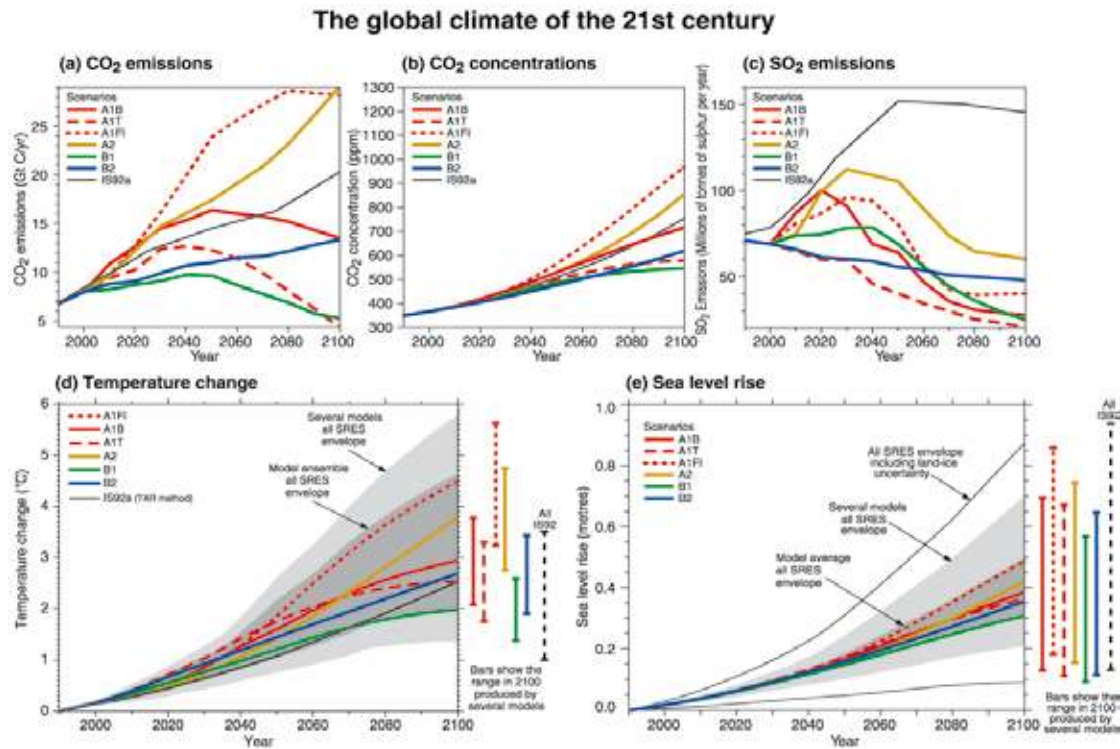


Shrimp farms cover the area where mangrove forests once stood, Bulungan, Indonesia. Copyright: Audrie Siahainenia

Although mangrove ecosystems have tremendous value for coastal communities and associated species, they are being destroyed at alarming rates. Over the last 50 years, about one-third of the world's mangrove forests have been lost (Alongi 2002). Human threats to mangroves include the overexploitation of forest resources by local communities, conversion into large scale development such as agriculture, forestry, salt extraction, urban development and infrastructure, and diversion of freshwater for irrigation (UNEP 1994). The greatest human threat to mangroves is the establishment of shrimp aquaculture ponds. Because mangroves are often viewed as wastelands, many developing countries are replacing these forests with agricultural land and/or shrimp aquaculture production (Franks and Falconer 1999). Shrimp aquaculture accounts for the loss of 20 to 50 percent of mangroves worldwide (Primavera 1997).

Projections suggest that mangroves in developing countries are likely to decline another 25 percent by 2025 (Ong and Khoon 2003). In some key countries like Indonesia, which has the world's largest intact mangroves, the projected rate of loss is even higher with 90 percent loss in some provinces like Java and Sumatra (Bengen and Dutton 2003). In addition to these anthropogenic threats, mangroves are also threatened by the impact of global climate change. Global climate change and concomitant effects such as changes in temperature and CO_2 , altered precipitation patterns, storminess, and eustatic sea-level rise as observed over recent decades, are due primarily to anthropogenic activities. Most of the observed warming over the last 50 years is attributed to an increase in greenhouse gas concentrations in the atmosphere (Houghton et al. 2001).

5 Potential Impacts of Climate Change



The global climate of the 21st century will depend on natural changes and the response of the climate system to human activities. Climate models project the response of many climate variables – such as increases in global surface temperature and sea level – to various scenarios of greenhouse gas and other human-related emissions. (a) shows the CO₂ emissions of the six illustrative SRES scenarios; (b) shows projected CO₂ concentrations; (c) shows anthropogenic SO₂ emissions; (d) and (e) show the projected temperature and sea level responses, respectively. Copyright: Houghton et al. 2001

Global climate change, specifically changes in temperature, CO₂, precipitation, hurricanes and storms, and sea level, combined with anthropogenic threats will threaten the resilience of mangroves. The impacts of climate change on mangroves will be summarized briefly below, although sea-level rise will be emphasized because it is projected to be the greatest climate change threat to mangroves. A more detailed description of these impacts on mangroves is provided in Appendix 1, and a summary of references that address climate related impacts on mangroves is listed in Appendix 2. Climate change impacts on mangroves will not occur in isolation; the response of mangroves to climate change will be a result of these impacts acting synergistically.

5.1 EFFECTS OF CHANGES IN TEMPERATURE

Since 1880, the Earth has warmed 0.6-0.8° C and it is projected to warm 2-6° C by 2100 mostly due to human activity (Houghton et al. 2001). Mangroves are not expected to be adversely impacted by the projected increases in sea temperature (Field 1995). Most mangroves produce maximal shoot density when mean air temperature rises to 25°C and stop producing leaves when the mean air temperature drops below 15°C (Hutchings and Saenger 1987). At temperatures above 25°C, some species show a declining leaf formation rate (Saenger and Moverly 1985). Temperatures above 35°C have led to thermal stress affecting

mangrove root structures and establishment of mangrove seedlings (UNESCO 1992). At leaf temperatures of 38-40°C, almost no photosynthesis occurs (Clough et al. 1982; Andrews et al. 1984).

Some scientists have suggested that mangroves will move poleward with increasing air temperatures (UNEP 1994; Field 1995; Ellison 2005). Although it is possible that some species of mangroves will migrate to higher latitudes where such range extension is limited by temperature, Woodroffe and Grindrod (1991) and Snedaker (1995) suggest that extreme cold events are more likely to limit mangrove expansion into higher latitudes.

5.2 EFFECTS OF CHANGES IN CO₂

Atmospheric CO₂ has increased from 280 parts per million by volume (ppmv) in the year 1880 to nearly 370 ppmv in the year 2000 (Houghton et al. 2001). Most atmospheric CO₂ resulting from fossil fuels will be absorbed into the ocean, affecting ocean chemistry. Increased levels of CO₂ are expected to enhance photosynthesis and mangrove growth rates (UNEP 1994). For example, increased levels of CO₂ significantly increased photosynthesis and the average growth rates in two Australian mangrove species, *Rhizophora stylosa* and *Rhizophora apiculata*, but only when grown at lower salinity levels (Ball et al. 1997).

One indirect impact on mangroves of increased temperature and CO₂ is the degradation of coral reefs caused by mass bleaching and impaired growth (Hoegh-Guldberg 1999). Damage to coral reefs may adversely impact mangrove systems that depend on the reefs to provide shelter from wave action.

5.3 EFFECTS OF CHANGES IN PRECIPITATION

Precipitation rates are predicted to increase by about 25 percent by 2050 in response to global warming. However, at regional scales, this increase

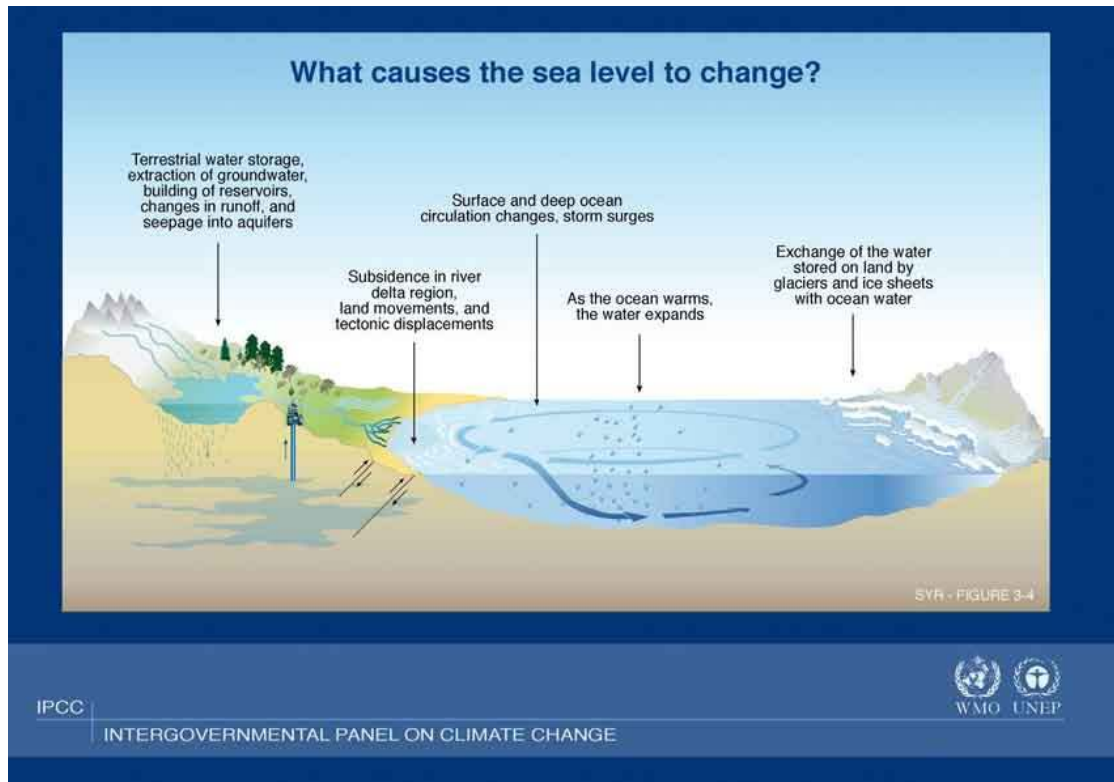
will be unevenly distributed with either increases or decreases projected in different areas (Knutson and Tuleya 1999; Walsh and Ryan 2000; Houghton et al. 2001). Changes in precipitation patterns caused by climate change may have a profound effect on both the growth of mangroves and their areal extent (Field 1995; Snedaker 1995).

Decreased precipitation results in a decrease in mangrove productivity, growth, and seedling survival, and may change species composition favoring more salt tolerant species (Ellison 2000, 2004). Decreased precipitation is also likely to result in a decrease in mangrove area, decrease in diversity, and projected loss of the landward zone to unvegetated hypersaline flats (Snedaker 1995). Increased precipitation may increase mangrove area, diversity of mangrove zones, and mangrove growth rates in some species (Field 1995). Increased precipitation may also allow mangroves to migrate and outcompete saltmarsh vegetation (Harty 2004).

5.4 EFFECTS OF CHANGES IN HURRICANES AND STORMS

According to the International Panel on Climate Change, there have been no reported trends observed in tropical storms, and no evidence of changes in the frequency or areas of storm formation, but they predicted that wind intensities will likely increase by 5 to 10 percent (Houghton et al. 2001). However, a more recent assessment indicates that tropical storms will indeed increase in frequency and/or intensity due to climate change (Trenberth 2005), posing an additional threat to mangroves.

Large storm impacts have resulted in mass mortality in 10 Caribbean mangrove forests in the last 50 years (Jimenez et al. 1985; Armentano et al. 1995). Cahoon et al. (2003) demonstrated that mass mangrove mortality in Honduras caused by a hurricane led to peat collapse which slowed



The level of the sea at the shoreline is determined by many factors in the global environment that operate on a great range of time scales, from hours (tidal) to millions of years (ocean basin changes due to tectonics and sedimentation). On the time scale of decades to centuries, some of the largest influences on the average levels of the sea are linked to climate and climate change processes. Copyright: Houghton et al. 2001

recovery rates following the disturbance. Model projections of South Florida mangroves suggest that an increase in hurricane intensity over the next century is likely to result in a decrease in the average height of mangroves (Ning et al. 2003). Major storms can also lead to a change in community structure based on a differential response to damage from the storm. Roth (1997) suggests that species proportions may shift because they have different rates of regeneration.

Projected increases in the frequency of high water events (Church et al. 2001, 2004) could affect mangrove health and composition due to changes in salinity, recruitment, inundation, and changes in the wetland sediment budget (Gilman et al. 2006). Storm surges can also flood mangroves and,

when combined with sea-level rise, lead to mangrove destruction. Flooding, caused by increased precipitation, storms, or relative sea-level rise may result in decreased productivity, photosynthesis, and survival (Ellison 2000). Inundation of lenticels in the aerial roots can cause the oxygen concentrations in the mangrove to decrease, resulting in death (Ellison 2004). Inundation is also projected to decrease the ability of mangrove leaves to conduct water and to photosynthesize (Naidoo 1983).

5.5 EFFECTS OF CHANGES IN SEA LEVEL

In the last century, eustatic sea level has risen 10-20 cm primarily due to thermal expansion of the oceans and melting of glacial ice caused by global warming (Church et al. 2001). Several climate

models project an accelerated rate of sea-level rise over coming decades (Church et al. 2001). Sea-level changes have also been influenced by tectonic and isostatic adjustments (i.e., ocean basin deformation and land subsidence or emergence) (Kennish 2002). During the 21st century, mean sea-level projections range from 0.09 to 0.88 m (Houghton et al. 2001).

Sea-level rise is the greatest climate change challenge that mangrove ecosystems will face (Field 1995). Geological records indicate that previous sea-level fluctuations have created both crises and opportunities for mangrove communities, and they have survived or expanded in several refuges (Field 1995). Mangroves can adapt to sea-level rise if it occurs slowly enough (Ellison and Stoddart 1991), if adequate expansion space exists, and if other environmental conditions are met.

5.5.1 MANGROVE ADAPTATIONS THAT HELP THEM SURVIVE SEA-LEVEL RISE

Mangroves have adapted special aerial roots, support roots, and buttresses to live in muddy, shifting, and saline conditions. Mangroves may adapt to changes in sea level by growing upward in place, or by expanding landward or seaward.



Mangrove pneumatophores emerging from sediment. Copyright: The Nature Conservancy

Mangroves produce peat from decaying litter fall and root growth and by trapping sediment in the water. The process of building peat helps mangroves keep up with sea-level rise. For example, in western Jamaica, mangrove communities were able to sustain themselves because their rate of sedimentation exceeded the rate of the mid-Holocene sea-level rise (ca. 3.8 mm/yr) (Hendry and Digerfeldt 1989).



Rhizophora with conspicuous prop-roots. Copyright: The Nature Conservancy

Mangroves can expand their range despite sea-level rise if the rate of sediment accretion is sufficient to keep up with sea-level rise. However, their ability to migrate landward or seaward is also determined by local conditions, such as infrastructure (e.g., roads, agricultural fields, dikes, urbanization, seawalls, and shipping channels) and topography (e.g., steep slopes). If inland migration or growth cannot occur fast enough to account for the rise in sea level, then mangroves will become progressively smaller with each successive generation and may perish (UNEP 1994).

5.5.2 ENVIRONMENTAL FACTORS THAT AFFECT MANGROVE RESPONSE TO SEA LEVEL

Understanding the impact of sea-level rise on mangrove ecosystems must take into account factors that affect the ecological balance of that ecosystem, such as the substrate type, coastal processes, local tectonics, availability of freshwater and sediment, and salinity of soil and groundwater (Belperio 1993; Semeniuk 1994; Blasco et al. 1996). Climatic variability (e.g., changes in rainfall and the frequency and intensity of cyclonic storms) can exacerbate the factors affecting mangrove response to sea level because it can alter the freshwater inflow to mangroves, the sediment and nutrient inputs, and the salinity regime. In an analysis of the impacts of sea-level rise on estuaries, Kennish (2002) highlights the importance of local conditions such as the size and shape of the estuary, its orientation to fetch and local currents, the areal distribution of wetlands, the geology of the neighboring watersheds, and land use in upland areas. Tidal range and sediment supply are two critical indicators of mangrove response to sea-level rise. Mangrove communities in macrotidal, sediment-rich areas (e.g., mangrove communities in northern Australia; Semeniuk 1994; Woodroffe 1995) may be better able to survive sea-level rise than those in micro-tidal sediment starved areas (e.g., mangroves in Caribbean islands; Parkinson et al. 1994). Carbonate settings are often associated with coral atolls and islands, where landward migration to escape the effects of sea-level rise is not possible and sediments are often limited; thus mangrove communities in carbonate islands are considered extremely vulnerable to sea-level rise (UNEP 1994). Therefore, sea-level rise is expected to decrease the geographic distribution and species diversity of mangroves on small islands with micro-tidal sediment-limited environments (IPCC 1997). Mangroves with access to allochthonous sediments, such as riverine mangroves, are more likely to survive sea-level rise than those

with low external inputs (Woodroffe 1990; Perinetta 1993). It is important to note that although access to sediment is critical for mangroves to survive sea-level rise, too much sediment (e.g., resulting from poor agricultural practices) can bury their pneumatophores and kill mangroves (Ellison and Stoddart 1991).

5.5.3 SPECIES RESPONSE TO SEA-LEVEL RISE

Individual mangrove species have varying tolerances of the period, frequency, and depth of inundation. Mangrove zones are related to shore profile, soils, and salinity, and changes in these can lead to changes in mangrove species composition. Different species may be able to move into new areas at different speeds, making some species capable of accommodating a higher sea-level rise rate than others (Semeniuk 1994).

6 Assessing Mangrove Vulnerability to Sea-level Rise

To build resilience into mangrove conservation plans, managers need to identify and protect mangroves that are more likely to survive sea-level

rise. The following table provides an assessment of mangrove vulnerability to sea-level rise based on environmental conditions.

Vulnerability	Local Conditions	Explanation
Most Vulnerable	Low relief islands	<ul style="list-style-type: none"> - low rates of sediment and peat accretion, particularly vulnerable to sea-level rise because they are subject to drought and wave erosion - expected to experience increased flooding, inundation and salinization of soils and freshwater (Shea et al. 2001).
	Lack of rivers	- lack of sediment and freshwater
	Carbonate settings	<ul style="list-style-type: none"> - often associated with atolls and islands, where landward migration to escape sea-level rise may not be possible - sediments are mostly locally derived
	Areas subsiding due to tectonic movements, groundwater extraction, or underground mining	- will experience higher sea-level rise and inundation
	Micro-tidal sediment starved environments (small Caribbean islands) (Ellison 1993)	- lack of sediment will lead to decreased geographic distribution and species diversity of mangroves (Houghton et al. 2001)
	Mangroves blocked by coastal development or steep topography	- unable to move inland when sea level rises
Least Vulnerable	Mangroves in deep sediment on high islands	<ul style="list-style-type: none"> - structurally stronger than mangroves in shallow sediment on low islands (Gillison 1980) and less vulnerable to storm surges than low islands (UNEP 1994) - high islands will be better adapted to survive predicted climate changes due to their larger surface areas, freshwater availability, better soils, and more diverse resources (Shea et al. 2001).
	Riverine mangroves	<ul style="list-style-type: none"> - receive large amounts of sediment from other areas (Woodroffe and Grindrod 1991) - most productive mangrove habitats due to high nutrient concentrations associated with sediment trapping (Ewel et al. 1998).
	Macro-tidal sediment rich environments (mangroves in northern Australia)	- access to sediment and strong tidal currents to redistribute sediment (Woodroffe and Grindrod 1991)
	Mangroves with room to move landward (backed by low-lying areas, salt flats, undeveloped areas)	- have the opportunity to expand inland when sea level rises
	Mangroves in remote areas	- have limited anthropogenic stresses and not blocked by coastal communities from moving landward
	Mangroves surrounded by flourishing dense mangrove forests	- have steady supply of propagules and seeds

7 Ten Strategies Managers Can Apply to Promote Resilience



Red mangrove roots, Canal Chiquimulilla, Guatemala. Copyright: Mangrove Action Project, Elaine Corets

While there is little that protected area managers can do to control large-scale threats like sea-level rise, there are at least ten strategies managers can apply that collectively hold promise to increase the viability of mangroves by enhancing their resilience.

- 1) Apply risk-spreading strategies to address the uncertainties of climate change.
- 2) Identify and protect critical areas that are naturally positioned to survive climate change.
- 3) Manage human stresses on mangroves.
- 4) Establish greenbelts and buffer zones to allow for mangrove migration in response to sea-level rise, and to reduce impacts from adjacent land-use practices.
- 5) Restore degraded areas that have demonstrated resistance or resilience to climate change.
- 6) Understand and preserve connectivity between mangroves and sources of freshwater and sediment, and between mangroves and their associated habitats like coral reefs and seagrasses.
- 7) Establish baseline data and monitor the response of mangroves to climate change.
- 8) Implement adaptive strategies to compensate for changes in species ranges and environmental conditions.

- 9) Develop alternative livelihoods for mangrove-dependent communities as a means to reduce mangrove destruction.
- 10) Build partnerships with a variety of stakeholders to generate the necessary finances and support to respond to the impacts of climate change.



Children around the Mangrove restoration project billboard, Winneba, Ghana. Copyright: IUCN, Michelle Laurie

7.1 SPREAD RISK BY IDENTIFYING AND PROTECTING REPRESENTATIVE MANGROVE HABITATS

To effectively spread the risk of losing mangroves to sea-level rise, managers should identify and protect representative species and habitats, replicates of these, and sources of seed to ensure replenishment following disasters. A range of mangrove habitats should be protected to capture different community types. These mangrove habitats may include mangrove fringe forests, overwash mangrove islands, riverine mangrove forests, and basin mangrove forests in areas with varying salinity, tidal fluctuation, and sea level (for classifications of mangrove types, see Appendix 5). Wherever possible, multiple samples of the best examples of each mangrove type should be included in protected area networks. Managers will need to develop a classification scheme of mangrove types and habitat zones, and categorize these

by their biodiversity and their ecosystem services. Maintaining biodiversity can enhance resilience if sufficient functional redundancy exists to compensate for species/habitat loss (Bellwood et al. 2004).

7.2 IDENTIFY AND PROTECT REFUGES

Managers should protect communities that have demonstrated resilience to climate stressors and/or are naturally positioned to survive global threats. For mangrove ecosystems, local conditions like the presence of sediment-rich, macrotidal environments, and the availability of freshwater to compensate for increased salinity, will aid mangrove survival and increase their resilience to sea-level rise. These areas should be incorporated into protected area design or otherwise incorporated into integrated coastal management programs. Managers also should identify and fully protect mangrove communities that have landward migration potential. Coastal land loss and human infrastructure and topography can limit the landward migration of mangroves. For example, population densities of more than 10 inhabitants per square km typically prevent wetland migration (Nicholls et al. 1999).

Mangrove areas that demonstrate persistence over time are important sites to protect. Indicators of persistence may include a range of small young and large old trees or mangrove roots with dense epibiont communities such as oysters, sponges, tunicates, and corals. Finally, mangrove forests with abundant mature trees producing a healthy supply of seeds and propagules should be protected as sources for colonizing new areas and repopulating areas damaged or destroyed by a disturbance (Nystrom and Folke 2001).

See Box 1 below for factors that may confer resilience and Figure 1 for a decision tree to aid site selection. However, these factors are only a guide and will need to be monitored over time and verified to ensure that the mangrove areas selected will survive climate changes.

Box 1

Mangrove resilience factors that inform site selection

Factors that allow for peat building to keep up with sea-level rise:

- Association with drainage systems including permanent rivers and creeks that provide freshwater and sediment
- Sediment rich-macrotidal environments to facilitate sediment redistribution and accretion
- Actively prograding coast and delta
- Natural features (bays, barrier islands, beaches, sandbars, reefs) that reduce wave erosion and storm surge

Factors that allow for landward migration:

- Mangroves backed by low-lying retreat areas (for example, salt flats, marshes, coastal plains) which may provide suitable habitat for colonization and landward movement of mangroves as sea level rises
- Mangroves in remote areas and distant from human settlements and agriculture, aquaculture, and salt production developments
- Mangroves in areas where abandoned alternate land use provides opportunities for restoration, for example, flooded villages, tsunami-prone land, unproductive ponds

Factors that enhance sediment distribution and propagule dispersal:

- Unencumbered tidal creeks and areas with a large tidal range to improve flushing, reduce ponding and stagnation, and enhance sediment distribution and propagule dispersal
- Areas with a large tidal range may be better able to adjust to increases in sea level due to stress tolerance
- Permanent strong currents to redistribute sediment and maintain open channels

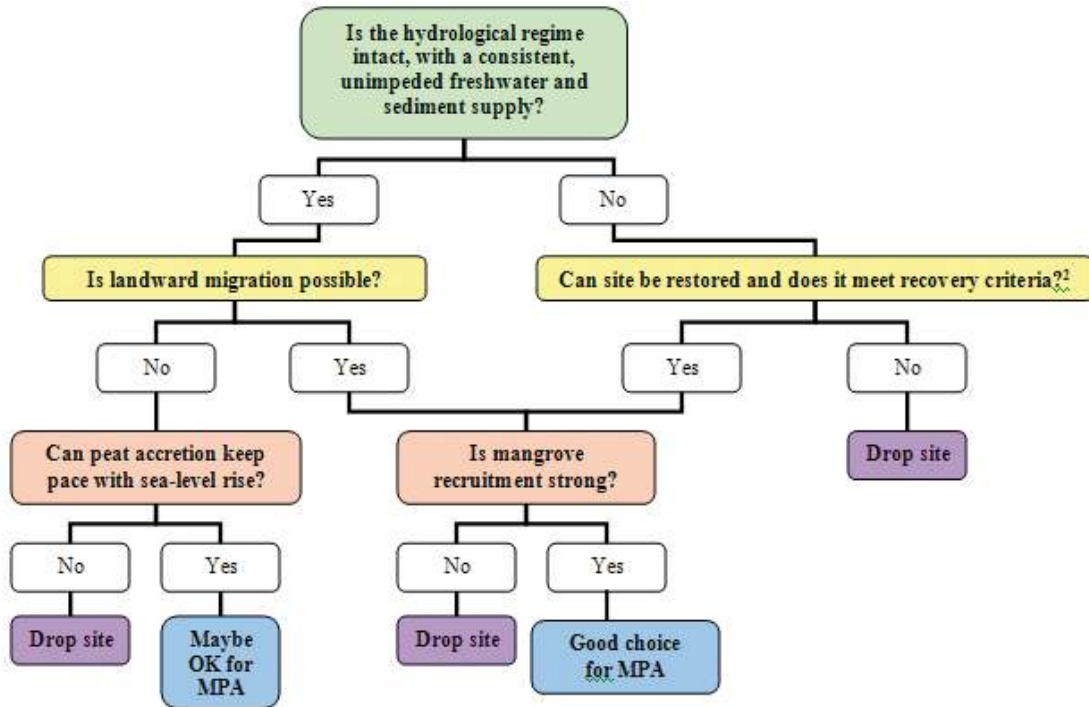
Factors that indicate survival over time:

- Diverse species assemblage and clear zonation over range of elevation (intertidal to dry land)
- Range in size from new recruits to maximum size class (location and species dependent)
- Tidal creek and channel banks consolidated by continuous dense mangrove forest (which will keep these channels open)
- Healthy mangrove systems in areas which have been exposed to large increases in sea level due to climate induced sea-level rise and tectonic subsidence

Factors that indicate strong recovery potential:

- Access to healthy supply of propagules, either internally or from adjacent mangrove areas
- Strong mangrove recruitment indicated by the presence, variety, and abundance of established mangrove propagules
- Close proximity and connectivity to neighboring stands of healthy mangroves
- Access to sediment and freshwater
- Limited anthropogenic stress
- Unimpeded or easily restorable hydrological regime
- Effective management regime in place such as the control of usual threats like dredging and filling, conversion to aquaculture ponds, construction of dams, roads, and dikes that disrupt hydrological regime etc.
- Integrated Coastal Management Plan or Protected Area Management Plan implemented

Figure 1: Decision tree to aid resilient site selection for mangroves¹



¹ This decision tree should be applied once candidate sites of high biodiversity have been selected using biological criteria

² See Box 1 for factors that indicate strong recovery potential

7.3 EFFECTIVE MANAGEMENT

To encourage resilience to global climate change, mangroves need to be protected from anthropogenic threats, because mangroves that are healthy will also be better able to adapt to global changes. Over half of mangrove areas are located within 25 km of urban centers inhabited by 100,000 or more people (Millenium Ecosystem Assessment 2005). Close proximity to urban areas poses threats like pollution, dyking, channelization, unregulated felling, conversion to aquaculture or agriculture, and other forms of coastal development. Therefore, managers should continue to reduce land-based threats to mangroves by improving land-use practices to decrease nutrient and sediment run-off, limit unregulated felling, eliminate the use of per-

sistent pesticides, and increase filtration of effluent to improve water quality in addition to mitigation of other anthropogenic threats. Support for community based projects to reduce anthropogenic stresses is important in conjunction with expanding our scientific understanding of the impacts of global change.

Anthropogenic threats to mangroves are expected to increase with climate change. Coastal communities may build seawalls or revetments in response to increased coastal erosion caused by sea-level rise. These structures may prevent coastal mangroves from retreating landward in response to sea-level rise. In addition, coastal population growth increases competition for space between mangroves and coastal peoples. Finally,



Mangrove Information Centre in Bali, Indonesia. Copyright: The Nature Conservancy

sea-level rise and coastal disasters may intensify demand for mangrove timber that is used to protect coastlines and rebuild houses damaged by inundation and erosion. Not only should managers mitigate existing anthropogenic threats, but they should also plan for these threats to grow with the increasing impacts of climate change on coastal communities.

7.4 ESTABLISH GREENBELTS AND BUFFER ZONES

Mangrove greenbelts can provide significant coastal protection from erosion and should be established along erosion-prone coastlines and riverbanks and in areas which experience significant damage from typhoons, tidal surges, cyclones, and geomorphic erosion (Macintosh and Ashton 2004). Greenbelts should be a minimum of 100 m, but preferably up to 500 m or 1 km (advocated in Mekong Delta which is subject to typhoons) at the open coast and 30-50 m along riverbanks and

lagoons, and >10 m on islands, creeks, and channels (Macintosh and Ashton 2002; Macintosh and Ashton 2004). In the Red River Delta in Vietnam, engineers estimate that an earthen sea dyke with rock facing will last about five years before it requires repair from wave damage, whereas the same sea dyke with a 100 m wide protective mangrove belt will last up to 50 years! (Macintosh and Ashton 2004).

It is also important to establish buffer zones bordering the seaward and landward margins of protected mangrove areas to provide a transition between human settlements with intensively used lands and waters and the protected area. The landward zones are more critical for mangroves in areas experiencing sea-level rise to enable landward expansion. The seaward zones are more critical for mangroves in areas where land is prograding to enable seaward expansion. To proactively plan for landward migration in areas where mangroves have the potential to expand, the ad-

adjacent land gradients should be used to determine how wide a buffer is necessary to accommodate the mangrove migration for different sea-level rise projections. The land-use practices surrounding buffer-zones should be “biodiversity-friendly” wherever possible (such as pesticide-free farming, sustainable forestry, and well-drained roadways and bridges) (Barber et al. 2004).

7.5 RESTORE DEGRADED CRITICAL AREAS THAT HAVE HIGH SURVIVAL PROSPECTS

Mangrove areas that are currently degraded but that meet resilience criteria (See Box 1) should be restored. Costs for restoring both vegetative cover and ecological functions of a mangrove area range from US\$225/ha to US\$216,000/ha (Lewis 2003). Hydrological restoration has been recognized as the most successful and cost-effective restoration approach (Lewis and Streever 2000). There are two main types of hydrological restoration: 1) restoring tidal hydrology through excavation or back-filling, and 2) reconnecting blocked areas to normal tidal influences (Lewis and Streever 2000).

Community restoration projects can be successful in restoring large numbers of mangrove trees. For example, in 1993 and 1995, at Gazi Bay, Kenya, more than 300,000 mangrove trees were planted in areas that were initially clearfelled for industrial fuelwood (Kairo 1995). In Tanga, northern Tanzania, mangroves have been replanted since 1997, with 107.4 ha of mangroves actively rehabilitated by 2004 (IUCN 2004).

One of the major causes of mangrove destruction in Southeast Asia and Latin America is the conversion of large areas of mangroves into shrimp ponds. Shrimp production has proven to be unsustainable in many regions, resulting in large areas of abandoned ponds, with as much as 70 percent of ponds abandoned after a period in production (Stevenson 1997). Shrimp ponds excavated in mangroves and now abandoned should be evalu-

ated for large-scale restoration. Shrimp-mangrove integrated farming systems in the Mekong Delta of Vietnam demonstrated that mangroves increased



Abandoned shrimp farm. Copyright: Mangrove Action Project, Alfredo Quarto

the productivity of shrimp aquaculture facilities; shrimp ponds with 30-50 percent mangrove coverage gave the highest annual economic returns (Binh et al. 1997).

Restoration of these areas may help create sustainable livelihoods for local communities and may also reduce the pressure on neighboring mangrove areas. Additionally, data suggest that there is a direct correlation between planting a variety of species to reforest an area and having diverse mangrove restoration objectives (Ellison 2000). Multi-species systems of mangroves seem to have greater ecological resilience (Blasco et al. 1996); thus, incorporating diverse objectives into conservation strategies can improve a mangrove forests’ resilience to climate change. According to Ellison (2000), mangrove restoration projects that take an ecosystem approach reflecting biodiversity and involving associated aquaculture or mariculture operations are more successful than approaches that only focus on trees.

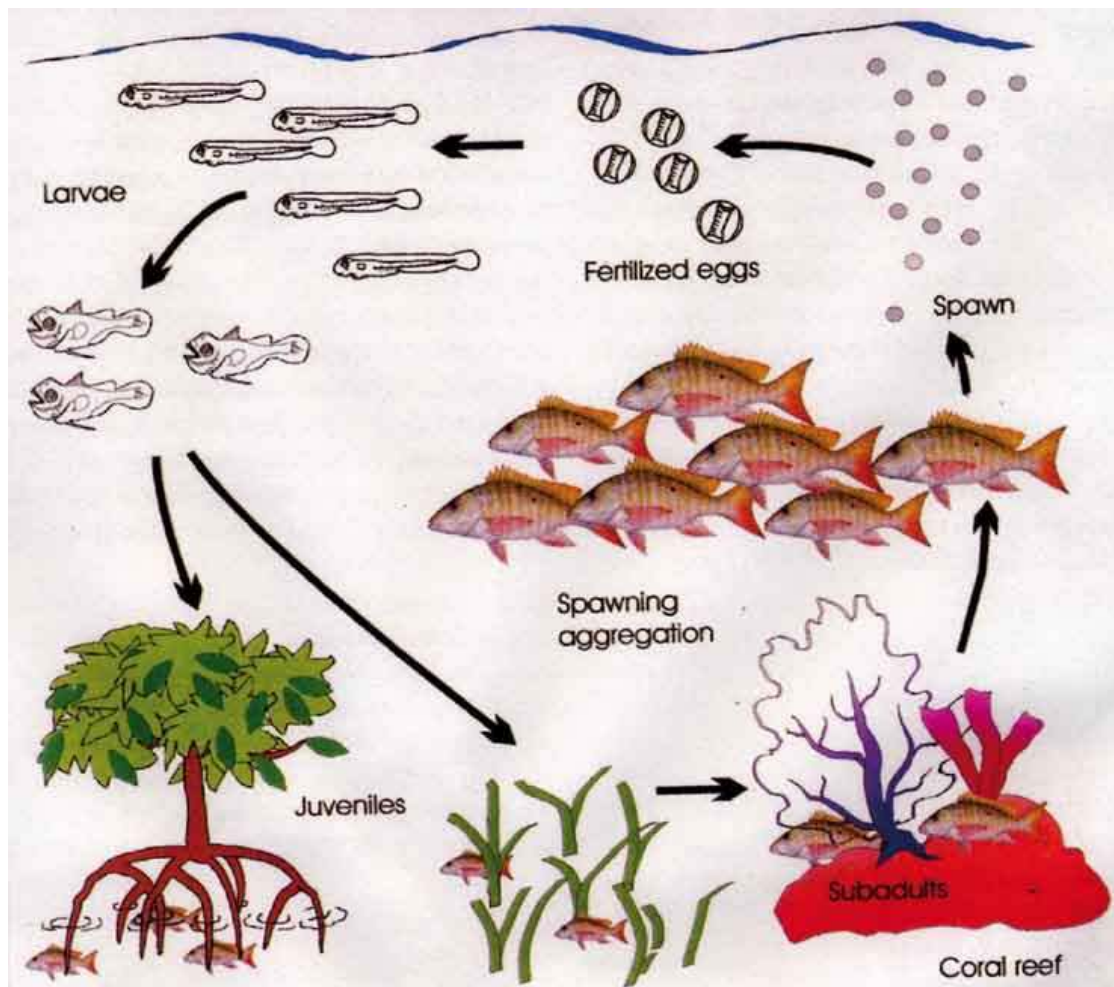
Managing mangroves for multiple uses makes financial sense because it can yield significantly greater economic return than a mangrove forestry plantation of a similar size (Lal 1990; Ruitenbeek 1994).

7.6 MAINTAIN CONNECTIVITY BETWEEN MANGROVES AND ASSOCIATED SYSTEMS

Connectivity between mangrove systems and upland water catchments should be maintained to ensure an adequate supply of sediment and freshwater. Healthy mangroves should be selected wherever they are connected through currents to

areas that may succumb to sea-level rise or to areas that would be suitable new areas for colonization following sea-level rise.

Mangroves, reefs, and fisheries often have a synergistic relationship, based on their connectivity (Mumby et al. 2004). Areas where mangroves benefit adjacent ecosystems by filtering sediments and pollutants or providing nursery habitats should be granted greater protection. Mangroves also stabilize sediments and trap heavy metals and nutrient rich run-off, thus improving the water quality for seagrasses, corals, and fish communities. Mangroves and seagrasses filter freshwater



Connectivity between mangrove, seagrass beds, and coral reefs. Copyright: Toledo Institute for Development and Environment

discharge from land, maintaining necessary water clarity for coral reef growth. Coral reefs buffer ocean currents and waves to create a suitably sheltered environment for mangroves and seagrasses. Mangroves also enhance the biomass of coral reef fish species. Mumby et al. (2004) suggest that mangroves are important intermediate nursery habitats between seagrass beds and patch reefs that increase young fish survival. Protected area managers should secure pathways of connectivity between mangroves, seagrass beds, and coral reefs to enhance resilience (Mumby et al. 2004) and fisheries.

7.7 ESTABLISH BASELINE DATA AND MONITORING PLAN

Because of the limited number of pristine mangrove forests and the increasing level of threat, establishing baseline data for mangroves is urgent and essential. Data should include a range of variables including: tree stand structure, tree abundance, species richness, and diversity; invertebrate abundance, richness, and diversity; primary production (biomass and litter), nutrient export; hydrologic patterns (Ellison 2000); and rates of sedimentation and relative sea-level rise. Human threats (e.g., sedimentation, coastal development, and deforestation) and existing management (e.g., traditional ownership, zoning system, policies controlling harvest and encroachment) should also be assessed. Baseline data can be used to develop vulnerability assessments that determine how areas will likely be affected by projected climate change (See Section 6).

To gauge the resilience of mangrove protected areas to current and future threat, mangrove ecosystems should also be monitored to determine the effects of global and anthropogenic stresses such as sea-level rise and over-exploitation of mangroves. Changes in nearshore chemistry (CO₂ levels and salinity), hydrography (sea level, currents, vertical mixing, storms and waves), and

temperature should be monitored over long time scales to determine climate changes and possible climate trends. This information should be analyzed to determine the resilience of mangrove protected areas to current and future threats. Flexible strategies and boundaries should be established and tracked to allow for adaptive management.

7.8 DEVELOP ADAPTIVE MANAGEMENT STRATEGIES

Climate changes such as sea temperature rise, sea-level rise, precipitation or salinity changes, and the frequency and intensity of storms will affect mangrove species distributions. If mangrove conservation strategies are to be successful in protecting species and habitats, they will need to adapt to the changing climate conditions. The ability to predict the location of future habitat sites, and build these potential sites into protected area design and adaptation, will be a crucial element of long-term planning to ensure sustainable protected areas in the face of global change. Flexible strategies and boundaries should be established and tracked to allow for adaptive management.

7.9 DEVELOP SUSTAINABLE AND ALTERNATIVE LIVELIHOODS FOR MANGROVE DEPENDENT HUMAN COMMUNITIES

While local stewardship and sustainable harvest of mangroves can be successful (Hussain and Ahmed 1994), encouraging local communities to develop alternative livelihoods that are less destructive than over-harvesting of mangroves or conversion to fish or shrimp ponds is a crucial step to mitigate mangrove deforestation.

Examples of alternative livelihoods include charcoal production from coconut shells instead of from mangroves as well as traditional honey harvesting in mangroves, which encourages agroforestry and conservation of existing mangrove forests (Nathanael 1964; Bandaranayake 1998). In Vietnam,



Boy harvesting shellfish in mangrove forest in the Chao Phaya Delta, Thailand. Copyright: Jeffrey McNeely

seaweed farming has been proposed as an income generating alternative to mangrove destruction (Crawford 2002). In North Sulawesi, Indonesia, sustainably harvested bamboo provides an alternative to over-harvesting of mangrove wood used in construction (Nugent 2003). Scientists and practitioners now recognize that governance and management frameworks must be developed that include diverse patterns of resource use to maintain social and ecological resilience (Adger et al. 2005). Alternative livelihood options and diverse income opportunities allow communities to be flexible to adapt to social, political, and economic changes.

7.10 BUILD CONSTITUENCY AND PARTNERSHIPS AT LOCAL, REGIONAL, AND GLOBAL SCALES

The tremendous challenges of global climate change require creative solutions and collaboration. Strong leadership is necessary to help mobilize support at local, regional, and global levels. Building global, regional, and local partnerships among industries (agriculture, tourism, water resource management) and conservation and infrastructure development can help alleviate the financial burdens of responding to large-scale threats like climate change (Shea et al. 2001).

A potential area of collaboration is between aid agencies and conservation groups. The Red Cross/Red Crescent societies are helping restore mangroves to enhance protection of the Red River Delta in Vietnam, one third of which is at risk of inundation due to sea-level rise (Hansen et al. 2003). Since 1997, the Red Cross/Red Crescent have planted 18,000 ha of mangroves along 100 km of coast. Marine resources seem to be increasing for local populations and habitat has been secured for over 109 species of bird (Hansen et al. 2003). Conservation groups and aid organizations can form partnerships with insurance industries that cover natural disasters. Insurance companies recognize the value of vulnerability assessments for their coverage. We should promote the value of risk mitigation in mangroves to insurance companies and seek funds for research to identify trends and vulnerable areas like those at risk of storm damage or flooding. Finally, it is also critical to understand the needs of local communities for sustained use of the mangroves. Ecosystem values of mangroves should be determined and communicated at the local and national level to encourage support for mangrove conservation.

8 Tools and Methods for Enhancing Mangrove Resilience



Mangrove harvest in the Sundarbans, Bangladesh. Copyright: IUCN, Jim Thorsell

Many tools and methods exist to help managers build resilience into their mangrove conservation strategies and track the historical response of mangrove forests to climate change. These will help scientists predict how mangrove systems will react to future changes.

8.1 LOW-TECH APPROACHES TO MEASURE VULNERABILITY TO SEA-LEVEL RISE

To determine communities and habitats vulnerable to sea-level rise, managers can compile survey and topographic maps with at least a 1-m contour interval. Aerial photographs and/or coastal maps that show coastal changes over time (e.g., beach erosion or variability, the mag-

nitude of and damage caused by flooding) can provide valuable historical records of changes in sea level. Tidal information, long-term data on relative sea-level rise, if available, and population density and other demographic data may be useful as well. Geographic Information Systems (GIS) can be used to overlay scenarios of sea-level rise with elevation and coastal development data to identify vulnerable areas (Klein et al. 2001). For a detailed explanation of mapping options, see Appendix 3. Local knowledge and newspaper accounts may also provide detailed information of how mangrove forests have changed historically, thus indicating which mangrove areas may be expanding or receding (UNESCO 1993).

Case Study in American Samoa

In American Samoa, a method has been developed to measure mangrove responses to projected relative sea-level rise (Gilman 2004):

- 1) Identify range of relative sea-level rise projections by comparing IPCC historical global sea-level rise data (Houghton et al. 2001) with local estimates from tide gauge data to determine a local correction for relative sea-level rise. This correction is then applied to projections of global sea-level rise to develop a range of local sea-level rise projections.
- 2) Identify the frequency and elevation of future extreme water events using tide gauge records.
- 3) Survey and map coastal habitat boundaries using aerial photos, satellite imagery, and maps.
- 4) Predict future change in elevation by determining sedimentation rates using sedimentation stakes, horizon markers, and radiochemical studies of sediment from cores.
- 5) Determine slope of upland adjacent to landward margin of mangroves and identify obstacles to landward migrations such as roads, seawalls, and buildings.
- 6) Estimate seaward erosion rate using historical time series of aerial photos, satellite images, and maps to reconstruct historical rate of erosion and project this rate into the future. Assess the correlation between shoreline mean erosion or accretion and relative sea-level change over the same time period to determine whether sea-level change is the dominant force causing change in shoreline position.
- 7) Map future boundary scenarios.

8.2 LOW-TECH APPROACHES TO MEASURE CHANGES IN SALINITY AND HYDROLOGY

Changes in salinity and hydrology are expected due to climate change and to anthropogenic impacts such as coastal development, groundwater extraction, and dredging. Salinity and hydrology changes are important to measure because they can affect the structure and function of mangrove ecosystems. To determine the salinity and hydrology in mangrove systems, a network of piezometer clusters can be installed at the site for continuous and manual measurements of salinity and water level (Drexler and Ewel 2001). For other low-tech methods for

measuring salinity and soil condition, see English et al. (1997).

8.3 LOW-TECH APPROACHES TO MEASURE CHANGES IN ELEVATION

Annual measurements of the soil elevation deficit (elevation change minus sea-level rise) will help determine mangrove ecosystem vulnerability to sea-level rise (Cahoon and Lynch 1997). Current rates of sedimentation can be measured using artificial soil marker horizon plots. Marker horizons measure vertical accretion which incorporates both sediment deposition and sediment erosion. Marker horizons can use sand, feldspar, brick dust and



Man reading an original design Surface Elevation Table (SET) in the mangrove forests in Florida. Copyright: Donald Cahoon

glitter, although Cahoon and Lynch (2003) recommend white feldspar as it is easily distinguishable from surrounding sediments. Marker horizons are often used with Surface Elevation Tables (SETs). SETs are used to monitor mangrove vertical accretion and subsidence and provide highly accurate and precise measurements (± 1.4 mm total error) of sediment elevation relative to sea-level rise (Cahoon et al. 2002a).

To determine how changes in sea-level rise will affect a particular area, it is important to understand the factors influencing surface elevation, such as sedimentation rate, groundwater flow, and biological productivity (Rogers 2004; Whelan et al. 2005).

Elevation changes are influenced by both surface and subsurface processes within the soil profile. Surface processes include sediment deposition and sediment erosion, and subsurface processes include root growth, decomposition, porewater flux, and compaction (Cahoon et al. 2002c). Most methods that measure surface elevation changes give only an absolute change in soil elevation and do not distinguish between elevation gain from accretion and elevation loss from subsidence (Whelan et al. 2005). However, SETs can be used with marker horizons to separate out surface accretion and subsurface expansion or compaction (Cahoon et al. 2003). According to Cahoon et al. (2003), if surface processes are controlling eleva-

tion change in mangroves, then elevation is controlled by erosion or sediment deposition, and if subsurface processes are controlling elevation, then it is more complicated to determine which process is dominant. New versions of the SET are able to determine where in the soil profile the influence is occurring (e.g., root zone, below root zone) (Cahoon et al. 2002b).

8.4 HIGH-TECH APPROACHES TO DETERMINE MANGROVE RESPONSE TO HISTORICAL SEA-LEVEL RISE

Pollen and radiocarbon analyses have been used to document environmental and mangrove dynamics during the Holocene (Wooller et al. 2004; Yulianto et al. 2004; and Versteegh et al. 2004). In a study in Belize, scientists extracted a 10 meter long mangrove peat core. They extracted and radiocarbon dated fragments of mangroves leaves preserved in the core (Wooller et al. 2004). The core provided an 8600 ¹⁴C year record of mangrove ecosystem changes. Pollen data from the core was used to determine changes in the floral composition of mangroves forests through the Holocene and indicated significant environmental changes such as disturbance from hurricanes or fluctuations in sea level. Changes in stand structure, which is related to changes in salinity, nutrient status, and sea level, were determined by analyzing variations in the stable carbon and nitrogen isotopes in the fossilized mangrove leaves. Historic sediment accumulation rates can also be calculated from ²¹⁰Pb profiles in vibracores (Walsh and Nittrouer 2004). ²¹⁰Pb is a naturally occurring radioactive isotope of lead that is used to date sediments.

In Western Port Bay, the rate of salt marsh decline caused by mangrove encroachment is lower than comparable sites in New South Wales (Rogers et al. 2005). According to Rogers et al. (2005), this may be attributed to the inverse relationship found between the degree of mangrove encroachment

and surface elevation increase. Rogers et al. (2005) used a combination of low-tech and high-tech methods to measure changes in mangrove and salt marsh habitat in New South Wales and Victoria, Australia. Historic sedimentation rates were measured using ²¹⁰Pb dating techniques, while feldspar horizon markers measured current sedimentation rates. SETs were set up in a network to measure sedimentation, subsidence, and sea-level rise. Rogers et al. (2005) compared the rate of subsidence with the eustatic sea-level trends to calculate relative sea-level rise for a number of sites. Relative sea-level rise was then compared to mangrove encroachment to determine mangrove and saltmarsh habitat changes over time.

8.5 HIGH-TECH APPROACHES TO PREDICT MANGROVE RESPONSE TO FUTURE SEA-LEVEL RISE

Although SETs and horizon markers provide useful information of short-term wetland elevation dynamics, they have several limitations that are overcome by site-specific computer models (Cahoon et al. 2002c). These models are able to consider long-term processes that influence wetland elevation and sediment collapse such as compaction and decomposition. In addition, the models are able to take elevation feedback mechanisms into account (e.g., elevation changes affect flooding patterns that alter sediment deposition rates and decomposition and self-generated primary production) (Cahoon et al. 2002c). Finally, vertical accretion and sediment elevation data can be used to initialize and calibrate the elevation models.

For managers to predict the landward migration of mangroves caused by sea-level rise, they will need to understand the relationship between landward slope and elevation in relation to tide range and extent (Ning et al. 2003). Models can be used to help managers assess mangrove vulnerability to sea-level rise. Relative Elevation Models (REMs)

have been used to project how mangroves will respond to increasing sea level (Cahoon et al. 2002c; Cahoon et al. 2003). According to Cahoon et al. (2002c), REMs simulate sediment dynamics (e.g., organic and mineral matter accretion, decomposition, and compaction) which produce changes in sediment characteristics (e.g., bulk density, organic matter volume and mass, and pore volume). The output of the model is sediment height. Sediment height is forced with eustatic sea-level rise and deep subsidence to determine wetland elevation relative to sea level.

Coastal flooding models are used to simulate projected sea-level rise in the Pamlico Sound in North Carolina (CSCOR 2005). The Center for Sponsored Coastal Ocean Research has combined a hydrodynamic model of water levels with a high resolution digital elevation model (DEM). This model will simulate long-term rises in water levels. Forecasts of ecological changes in coastal wetland and forested areas will be incorporated into the model. The model will be used to develop maps and tools that help managers identify projected shoreline changes and predict ecosystem impacts. With this information, managers can develop proactive mitigation strategies to address future climate changes.

The U.S. Geological Survey uses integrated landscape models that integrate the landscape and forest scales like the SELVA-MANGRO (Spatially Explicit Landscape Vegetation Analysis - spatially explicit stand simulation model constructed for mangrove forests) to predict the future mangrove forest migration in the Everglades under rising sea level (Ning et al. 2003). SELVA tracks predicted landscape changes, both biotic and abiotic, and calculates probability functions of disturbance including sea-level rise, hurricanes, and lightning. This information is sent to the MANGRO model, which sends information on mangrove stand structure and composition to SELVA. Outputs from the model include maps of the impacts of sea-level

rise on mangrove species composition and forest migration. The model suggests that mangrove habitats will increase and freshwater marsh and swamp habitats will decrease under anticipated climate change scenarios in South Florida; because sea-level rise will cause mangroves to encroach onto the Everglades slope, displacing freshwater marsh and swamp habitats (Ning et al. 2003).

9 A Framework for Action



Bird and crocodile-spotting tour in Hull River in Far North Queensland. Eco-tourism tours take tourists on educational tours of the mangrove. Copyright: Stephen MacGowan.

Houghton et al. (2001) estimate that by 2080, human reclamation of wetlands will represent a 37 percent loss of global wetlands without including the impacts of sea-level rise. The effects of sea-level rise boost this percentage an additional 25 percent; thus by 2080, we will have lost over 60 percent of the world's coastal wetlands. With global changes affecting all countries, there is an opportunity for international collaboration on wetlands conservation. Species and habitat shifts are not confined by political boundaries and countries will need to develop local, regional, and global strategies to safeguard valuable resources like mangroves. We can either invest in increasing our understanding of what factors contribute to mangrove survival, or we need to look elsewhere to replace all of the economic, food, and coastal protection benefits that mangroves provide. Despite the dire predictions, there is

still room for optimism. A synthesis of what we already know about mangrove risk and mangrove vulnerability allows one to construct a practical decision tree that can help managers use resilience criteria to select protected areas (Figure 1). It starts from the assumption that certain biological criteria for site selection can and should be used to select candidate sites with high biodiversity value. These candidate sites are then evaluated for their probability of survival, specifically with respect to sea-level rise. The decision tree includes restoration as a major option because it is unlikely we will find enough undamaged sites that also have the attributes associated with reduced vulnerability. To be successful in a changing world, conservation strategies must strive to achieve the complementary key goals of maintaining biodiversity, promoting ecosystem values, and enhancing resilience.

The Intergovernmental Panel on Climate Change scenarios for sea-level rise (Houghton et al. 2001) pose a tremendous threat to coastal cities and recreational destinations. We must find ways to address those threats at all levels, from less carbon dependent economies to climate adapted coastal management. The natural resilience of mangroves to climate change provides hope for their long-term survival. Global changes will challenge us to develop forward-looking strategies and respond with innovative solutions. We must take action now based on the best available information and manage adaptively to enable periodic correction in strategies as knowledge and science develop. The future of mangroves is uncertain and demonstrated leadership and commitment is essential to ensure their long-term survival. The resilience principles in this paper outline a framework for action. What are needed now are demonstration projects to test, learn, adapt and refine these principles.

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Glossary

Accretion: deposition of material by sedimentation which increases land area

Allochthonous: originating from outside a system

Anthropogenic: of, relating to, or resulting from the influence of humans on nature

Biomass: the total mass of all living organisms or of a particular set of organisms in an ecosystem or at a trophic level in a food chain; usually expressed as a dry weight or as the carbon, nitrogen, or caloric content per unit area

Catchment: the area drained by a river or body of water

Channelization: the straightening of rivers or streams by means of an artificial channel

Eustatic: worldwide change in sea level such as that caused by tectonic movements or by the growth or decay of glaciers

Fetch: the distance along open water or land over which the wind blows; the distance traversed by waves without obstruction

Geographic Information System (GIS): an organized collection of computer hardware, software, geographic data, and personnel designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information

Geomorphology: the study of landforms on a planet's surface and of the processes that have fashioned them

Holocene: the present, post-Pleistocene geologic epoch of the Quaternary period, including the last 10,000 years; the recent or Post-glacial period

Hydrology: the study of the movement of water from the sea through the air to the land and back to the sea; the properties, distribution, and circulation of water on or below the Earth's surface and in the atmosphere

Lenticels: the breathing pores in the outer bark of woody plants

Mangal: MacNae (1968) proposed this term to refer to the mangrove community, as opposed to the constituent plant species

Mangrove: tree, shrub, palm or ground fern, generally exceeding more than half a meter in height, and which normally grows above mean sea level in the intertidal zones of marine coastal environments, or estuarine margins. The term "mangrove" can refer to either the constituent plants of tropical intertidal forest communities or to the community itself

Phenology: the study of the relationship between climate and the timing of periodic natural phenomena such as migration of birds, bud bursting, or flowering of plants

Pneumatophores: aerial roots of a mangrove that typically rises from the soil into the air above the low tide level, thereby allowing the plant to obtain oxygen directly from the air ("breathing roots")

Propagules: any part of a plant that can give rise to a new individual and aids in dispersal of the species

Recruitment: the influx of new members into a population by reproduction or immigration

Refugia: an area of relatively unaltered climate that is inhabited by plants and animals during a period of continental climatic change (e.g., glaciation) and remains as a center of relict forms from which a new dispersion and speciation may take place after climatic readjustment. Refugia are secure areas that are protected by natural factors and human intervention from a variety of stresses. They function as reliable sources of seed

Remote sensing: methods for gathering data on a large or landscape scale which do not involve on-the-ground measurement, especially satellite photographs and aerial photographs; often used in conjunction with Geographic Information Systems

Replication: the process by which multiple samples of any habitat types are secured in a network of protected areas. Replication helps to spread the risk of any large-scale event destroying all protected examples of any habitat type

Representation: the inclusion of a full range of habitat types into a protected area system. Representation of all habitat types helps to ensure that the full complement of species for that habitat type is protected

Resilience: the ability of a system to undergo, absorb, and respond to change and disturbance, while maintaining its functions

Resistance: the capacity of an organism or a tissue to withstand the effects of a harmful environmental agent

Surface Elevation Tables (SETs): portable mechanical leveling device for measuring the relative elevation of wetland sediments. SETs can be used to monitor mangrove vertical accretion and subsidence and provide highly accurate and precise measurements (+/- 1.4 mm total error) of sediment elevation relative to sea-level rise

Transpiration: the loss of water vapor from a plant to the outside atmosphere, mainly through the breathing pores on the surface of a plant's leaves and the lenticels of stems

Appendix 1:

Detailed description of climate change impacts on mangroves



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1. EFFECTS OF CHANGES IN TEMPERATURE

Since 1880, the Earth has warmed 0.6-0.8° C and it is projected to warm 2-6° C by 2100 mostly due to human activity (Houghton et al. 2001). The projected increases in atmospheric and sea temperature are not expected to adversely impact mangroves, because the rate of projected change is considerably less than the diurnal oscillations in temperature at the limits of mangrove range (Field 1995). Global mangrove distributions are limited by temperature in subtropical latitudes at the 16°C isotherm for air temperature of the coldest month (Chapman 1977), the 24°C sea surface isotherm for the warmest month (Pernetta 1993), and at the margins of incidence of ground frost (Ellison 2005).

Some scientists have suggested that mangroves will move poleward with increasing air temperatures (UNEP 1994; Field 1995; Ellison 2005). Although it is possible that some species of mangroves will migrate to higher latitudes where such range extension is limited by temperature, Woodroffe and Grindrod (1991) suggest that extreme cold events are more likely to limit mangrove expansion into higher latitudes. Snedaker (1995) also argues against the hypothesis that mangroves will move poleward with increases in global temper-

ature. Using the example of Florida mangroves, Snedaker describes the expansion northward of the northern limit of mangroves along the east coast of the United States in the 1970s. However, several severe freezes in 1977, 1981, and 1989 caused massive mangrove mortality resulting in reduction in mangrove area and reduction in the north range limit.

Temperature affects mangrove photosynthesis, water loss, transpiration, and salt loss (Pernetta 1993). Most mangroves produce maximal shoot density when mean air temperature rises to 25°C and stop producing leaves when the mean air temperature drops below 15°C (Hutchings and Saenger 1987). Despite a greater production of stilt roots per unit area for *Rhizophora mangle* in Puerto Rico due to a 5°C increase in temperature; the temperature stress resulted in the production of more, but significantly smaller leaves for *R. mangle* (Canoy 1975). Temperatures above 35°C have led to thermal stress affecting mangrove root structures and establishment of mangrove seedlings (UNESCO 1992). At temperatures above 25°C, some species show a declining leaf formation rate (Saenger and Moverly 1985); and at leaf temperatures of 38-40°C, almost no photosynthesis occurs (Clough et al. 1982; Andrews et al.

1984). In Florida mangroves, little or no photosynthesis occurred at 40°C and the temperature optima for photosynthesis was below 35°C (Moore et al. 1972). Increases in temperature are predicted to benefit Pacific Islands Developing Countries, because warming is projected to increase the diversity of marginal mangroves at higher latitudes, currently home to only *Avicennia* species (Burns 2001). In the Pacific Islands, warming is projected to facilitate mangrove expansion into saltmarsh communities (Burns 2001). Mangrove species in China have demonstrated varying thermal tolerances. Li and Lee (1997) divided the mangrove species in China into three classes based on thermal tolerance: 1) cold-resistant eurytopic species (e.g., *Kandelia candel*, *Avicennia marina* and *Aegiceras corniculatum*); 2) cold-intolerant (thermophilic) stenotopic species (e.g., *Rhizophora mucronata*, *R. apiculata*, *Lumnitzera littorea*, *Nypa fruticans* and *Pemphis acidula*); and 3) thermophilic eurytopic species, (e.g., *R. stylosa*, *Bruguiera sexangula*, *B. gymnorrhiza*, *Excoecaria agallocha* and *Acrostichum aureum*; Zhang and Lin 1984).

Despite the uncertainties of how temperature changes will affect the species composition or the seasonal patterns of reproduction and flowering of mangroves, an increase in sea-surface and air temperatures would likely benefit mangroves living near the poleward limits of current distributions; leading to increased species diversity, greater litter production, and larger trees in these mangrove systems (Edwards 1995). Temperature increases may impact mangroves by changing the seasonal patterns of reproduction and the length of time between flowering and the fall of mature propagules (UNEP 1994; Ellison 2000).

Soil temperature change is expected to be of the same magnitude and rate of increase as that of sea surface temperature, although variations in soil temperature are generally much less than those of air temperature based on the large capac-

ity of saturated soils to retain heat (UNEP 1994). Therefore, even if soil temperatures increase, it is not likely to adversely affect mangroves (UNEP 1994). Increased sediment temperature may also cause increased growth rates of bacteria resulting in increased rates of nutrient recycling and regeneration.

2. EFFECTS OF CHANGES IN CO₂

Atmospheric CO₂ has increased from 280 parts per million by volume (ppmv) in the year 1880 to nearly 370 ppmv in the year 2000 (Houghton et al. 2001). Most atmospheric CO₂ resulting from fossil fuels will be absorbed into the ocean affecting ocean chemistry. According to UNEP (1994), the efficiency of mangrove water use will be enhanced, and there will be specific species variation in response to elevated CO₂. Due to the increase in water use efficiency, mangroves in arid regions may benefit because decreased water loss via transpiration will accompany CO₂ uptake (Ball and Munns 1992). If salinity increases in arid regions, then this advantage may be lost, because increases in CO₂ do not affect mangrove growth when salinity is too high for a species to maintain water uptake.

Increases in CO₂ are not likely to cause mangrove canopy photosynthesis to increase significantly (UNEP 1994). However, in an experiment testing the effects of humidity, salinity, and increased CO₂ on two Australian mangrove species, *Rhizophora stylosa* and *Rhizophora apiculata*, photosynthesis did increase significantly with increased levels of CO₂ (Ball et al. 1997). The mangroves were grown in glasshouses for 14 weeks with different combinations of atmospheric CO₂ (340 and 700 ppm), relative humidity (43 and 86 percent), and salinity (25 and 75 percent of seawater) to determine the effects of these variables on their development and growth (Ball et al. 1997). Although *Rhizophora stylosa* has a slower relative growth rate and

greater salt tolerance than *Rhizophora apiculata*, the scientists concluded that elevated CO₂ significantly increased rates of net photosynthesis in both mangrove species, but only when grown at the lower salinity level. In addition, while increased CO₂ levels did not significantly affect the relative growth rate of either species, the average growth rates of both species increased with atmospheric CO₂ enrichment in the lower salt environment (Ball et al. 1997). These scientists postulated that increased levels of CO₂ might allow these two mangrove species to expand into areas of greater aridity, thus increasing species diversity in those regions.

Snedaker and Araújo (1998) exposed four mangrove species *Rhizophora mangle*, *Avicennia germinans*, *Laguncularia racemosa*, and *Conocarpus erectus* to increased CO₂ (361-485 ppm). All four species demonstrated significant decreases in stomatal conductance and transpiration and an increase in instantaneous transpiration efficiency. Only *L. racemosa* demonstrated a significant decrease in net primary productivity when exposed to increased CO₂. Snedaker and Araújo (1998) suggest that increased levels of CO₂ on a global scale may result in a competitive disadvantage of *L. racemosa* in mixed mangrove communities relative to the other species whose rates of net primary productivity are not significantly affected by increases in CO₂. The results of this study indicate that global increases in CO₂ may result in a competitive advantage of mangroves in arid regions due to their ability to minimize water use during periods of water stress while maintaining relatively high rates of CO₂ uptake (Snedaker and Araújo 1998).

Farnsworth et al. (1996) analyzed the effects of doubled levels of CO₂ on *Rhizophora mangle* seedlings. The seedlings demonstrated significant increases in biomass, total stem length, branching activity, and total leaf area compared to seedlings grown in normal levels of CO₂. In this study, re-

production of *Rhizophora mangle* was achieved after only one year of growth in a high CO₂ environment, whereas it typically takes a full two years before they are able to reproduce in the field; thus elevated CO₂ also appeared to accelerate maturation in addition to growth. However, Ellison and Farnsworth (1996) predict that whether increased atmospheric CO₂ results in enhanced growth of mangroves, it will likely not be enough to compensate for the negative impacts of sea-level rise.

One indirect impact on mangroves of increased temperature and CO₂ is the degradation of coral reefs caused by mass bleaching and impaired growth (Hoegh-Guldberg 1999). Damage to coral reefs may adversely impact mangrove systems that depend on the reefs to provide shelter from wave action.

3. EFFECTS OF CHANGES IN PRECIPITATION

Precipitation rates are predicted to increase by about 25 percent by 2050 in response to global warming. However, at regional scales, this increase will be unevenly distributed with either increases or decreases projected in different areas (Knutson and Tuleya 1999; Walsh and Ryan 2000; Houghton et al. 2001). Changes in precipitation patterns caused by climate change may have a profound effect on both the growth of mangroves and their areal extent (Field 1995; Snedaker 1995).

Regional climate models predict that precipitation will decrease in certain areas (e.g., Central America during the months of winter, Australia in winter) (Houghton et al. 2001). Decreased precipitation results in less freshwater surface water input to mangroves and less water input into the groundwater which could increase salinity. Increases in salinity in the soil result in increased salt in mangrove tissues. Increased salinity and lack of freshwater is likely to result in a decrease in mangrove productivity, growth, and seedling survival, and may change species composition favoring more salt tolerant species (Ellison 2000, 2004). For

example, in Australia, mangroves are stunted, of narrower margins, and interrupted by salt flats in areas of lower rainfall mainly due to salt stress (Ellison 2000). Decreased rainfall, combined with the increase in evaporation in arid areas, is also likely to result in a decrease in mangrove area, decrease in diversity, and projected loss of the landward zone to unvegetated hypersaline flats (Snedaker 1995).

In areas where rainfall is projected to increase due to climate change (e.g., northern mid-latitude regions in winter and in the Pacific Islands north of 17°S; Houghton et al. 2001; Campbell 1996), mangrove area and diversity of mangrove zones and growth rates may increase (Ellison 2000). Maximal growth of mangroves has been linked to low salinities (Burchett et al. 1984; Clough 1984), thus if precipitation increases and results in decreased soil salinity, mangrove growth rates may increase in some species (Field 1995). In Australia, mangroves grow taller, more productive, and more diverse in areas of higher rainfall (Ellison 2000). Harty (2004) suggests that increases in rainfall reduce salinity levels within saltmarshes which allows mangroves to migrate and outcompete saltmarsh vegetation. This trend of mangrove transgression into saltmarsh habitat has been observed in southeast Australia due to increases in precipitation (Rogers et al. 2005).

4. EFFECTS OF CHANGES IN HURRICANES AND STORMS

According to the International Panel on Climate Change, there have been no reported trends observed in tropical storms, and no evidence of changes in the frequency or areas of storm formation, but they predicted that wind intensities will likely increase by 5 to 10 percent (Houghton et al. 2001). However, a more recent assessment indicates that tropical storms will indeed increase in frequency and/or intensity due to climate change (Trenberth 2005), posing an additional threat to

mangroves. A 5-10 percent increase in hurricane activity is projected by around 2050 (Giorgi et al. 2001), although much uncertainty exists based on the coarse resolution of the general circulation models (Walsh et al. 2004). In 1998, Hurricane Mitch destroyed 97 percent of the mangroves in Guanaja in Honduras (Cahoon and Hensel 2002). Large storm impacts have resulted in mass mortality in 10 Caribbean mangrove forests in the last 50 years (Jimenez et al. 1985; Armentano et al. 1995). Cahoon et al. (2003) demonstrated that mass mangrove mortality in Honduras caused by a hurricane led to peat collapse which slowed recovery rates following the disturbance. Model projections of South Florida mangroves suggest that an increase in hurricane intensity over the next century is likely to result in a decrease in the average height of mangroves (Ning et al. 2003).

Projected increases in the frequency of high water events (Church et al. 2001, 2004) could affect mangrove health and composition due to changes in salinity, recruitment, inundation, and changes in the wetland sediment budget (Gilman et al. 2006). Storm surges can also flood mangroves and, when combined with sea-level rise, lead to mangrove destruction. In Florida, acres of black mangroves (*Avicennia germinans*) suffocated when a storm generated flood raised the water depth and sea-level rise prevented this water from subsiding (Lollar 2004). Flooding, associated with heavy rains of the 1998 El Niño, resulted in mortality of mangrove forests in the Rufiji Delta in Tanzania (Ertfemeijer and Hamerlynck 2005). Flooding, caused by increased precipitation, storms, or relative sea-level rise may result in decreased productivity, photosynthesis, and survival (Ellison 2000). Inundation of lenticels in the aerial roots can cause the oxygen concentrations in the mangrove to decrease, resulting in death (Ellison 2004). Inundation is also projected to decrease the ability of mangrove leaves to conduct water and to photosynthesize (Naidoo 1983).

Major storms can also lead to a change in community structure based on a differential response to damage from the storm. For example, Hurricane Andrew heavily damaged large *Laguncularia racemosa* and did not greatly impact smaller *Rhizophora mangle*; this has led to a shift in species distributions in some areas (Baldwin et al. 1995). In this study, Baldwin et al. (1995) demonstrated that Florida mangroves that experienced moderate hurricane damage regenerated primarily through *Rhizophora* advance recruits and developed into single-species stands; whereas in severely damaged forests, mixed seedling recruitment of *Avicennia*, *Laguncularia*, and herbaceous species led to mixed-species stands. According to Rey et al. (1990), *Rhizophora mangle* may replace *Avicennia germinans* in Florida due to storms and hurricanes that cause pneumatophore submergence, because *R. mangle* can tolerate pneumatophore submergence longer than *A. germinans*. Model projections of mangroves in South Florida also supported the idea that *R. mangle* will increase in proportion due to out-competing more vulnerable species (Ning et al. 2003). Roth (1997) suggests that species proportions may shift because they have different rates of regeneration.

Hurricanes may mitigate the impacts of sea-level rise by depositing sediment in mangrove forests. Alternatively, hurricanes may exacerbate the impacts of sea-level rise by uprooting trees, leaving sediment unprotected and vulnerable to erosion.

5. EFFECTS OF CHANGES IN SEA LEVEL

In the last century, eustatic sea-level has risen 10-20 cm primarily due to thermal expansion of the oceans and melting of glacial ice caused by global warming (Church et al. 2001). Several climate models project an accelerated rate of sea level rise over coming decades (Church et al. 2001). Sea-level changes have also been influenced by tectonic and isostatic adjustments (i.e., ocean basin deformation and land subsidence or emer-

gence) (Kennish 2002). Past sea-level change has been measured by tide gauges at different locations around the world. Tide gauges are not evenly distributed around the globe which biases the data and does not provide an accurate picture of the global pattern of sea-level change (Cabanes et al. 2001). However, despite the uncertainties in tide gauge data, scientists estimate that the global average sea level rose at a rate of 1.0 to 2.0 millimeters (mm)/year during the 20th century (Houghton et al. 2001). This increase is an order of magnitude larger than the average rate over the previous several thousand years (CSIRO 2001). During the 21st century, mean sea-level projections range from 0.09 to 0.88 m (Houghton et al. 2001).

In addition to the uncertainties of global sea-level rise, uncertainties also exist for how regions will experience different rates and magnitudes of sea-level rise. Regional sea-level rise is affected by tectonic movements that can cause land subsidence or uplift. Natural and human induced sediment compaction can also exacerbate the impacts of sea-level rise. Humans contribute to land subsidence through coastal development that causes deficits in the sediment budget, shipping channels that cause bank erosion, groundwater or oil extraction that causes submergence, and dredging and mining that causes losses of land. The combination of global sea-level rise and local impacts that cause land subsidence threaten the existence of mangroves worldwide.

Sea-level rise is the greatest climate change challenge that mangrove ecosystems will face (Field 1995). Geological records indicate that previous sea-level fluctuations have created both crises and opportunities for mangrove communities, and they have survived or expanded in several refuges (Field 1995). Mangroves can adapt to sea-level rise if it occurs slowly enough (Ellison and Stoddart 1991), if adequate expansion space exists, and if other environmental conditions are met.

MANGROVE ADAPTATIONS THAT HELP THEM SURVIVE SEA-LEVEL RISE

Mangroves have adapted special aerial roots, support roots, and buttresses to live in muddy, shifting, and saline conditions. Mangroves may adapt to changes in sea level by growing upward in place, or by expanding landward or seaward. Mangroves produce peat from decaying litter fall and root growth and by trapping sediment in the water. The process of building peat helps mangroves keep up with sea-level rise. For example, in western Jamaica, mangrove communities were able to sustain themselves because their rate of sedimentation exceeded the rate of the mid-Holocene sea-level rise (ca. 3.8 mm/yr) (Hendry and Digerfeldt 1989).

Mangroves can expand their range despite sea-level rise if the rate of sediment accretion is sufficient to keep up with sea-level rise and if migration is not blocked by local conditions, such as infrastructure (e.g., roads, agricultural fields, dikes, urbanization, seawalls, and shipping channels) and topography (e.g., steep slopes). A study in the Adelaide river area of the Northern Territory in Australia shows that the landward zone of mangroves doubled in size in the last twenty years (Jones 2002). Thus, inland wetland migration can offset the losses of coastal wetlands in areas that have low-lying coastal uplands (Houghton et al. 2001). For example, 3807 ha of mangroves in Moreton Bay, Australia were lost due to a combination of natural causes and mangrove clearing over a 24-year period (Manson et al. 2003). However, the majority of these losses were offset by the establishment of 3590 ha of new mangroves which settled mostly on the landward edge of existing mangroves and by the improved management of coastal wetlands in the Greater Brisbane Area (Dutton 1992). If inland migration or growth cannot occur fast enough to account for the rise in sea level, then mangroves will become progressively smaller with each successive generation and may perish (UNEP 1994).

ENVIRONMENTAL FACTORS THAT AFFECT MANGROVE RESPONSE TO SEA LEVEL

Understanding the impact of sea-level rise on mangrove ecosystems must take into account factors that affect the ecological balance of that ecosystem, such as the substrate type, coastal processes, local tectonics, availability of freshwater and sediment, salinity of soil and groundwater (Belperio 1993; Semeniuk 1994; Blasco et al. 1996). Climatic variability (e.g., changes in rainfall and the frequency and intensity of cyclonic storms) can exacerbate the factors affecting mangrove response to sea level because it can alter the freshwater inflow to mangroves, the sediment and nutrient inputs, and the salinity regime. In an analysis of the impacts of sea-level rise on estuaries, Kennish (2002) highlights the importance of local conditions such as the size and shape of the estuary, its orientation to fetch and local currents, the areal distribution of wetlands, the geology of the neighboring watersheds, and land use in upland areas. Thus, vulnerability assessments will be important for determining which areas are more likely to survive despite climatic changes (See Section 6).

Tidal range and sediment supply are two critical indicators of mangrove response to sea-level rise. Mangrove communities in macrotidal, sediment-rich areas (e.g., mangrove communities in northern Australia; Semeniuk 1994; Woodroffe 1995) may be better able to survive sea-level rise than those in micro-tidal sediment starved areas (e.g., mangroves in Caribbean islands; Parkinson et al. 1994). Carbonate settings are often associated with coral atolls and islands, where landward migration to escape the effects of sea-level rise is not possible and sediments are often limited; thus mangrove communities in carbonate islands are considered extremely vulnerable to sea-level rise (UNEP 1994). Therefore, sea-level rise is expected to decrease the geographic distribution and species diversity of mangroves on small islands with micro-tidal sediment-limited environments (IPCC

1997). Mangroves with access to allochthonous sediments, such as riverine mangroves, are more likely to survive sea-level rise than those with low external inputs (Woodroffe 1990; Pernetta 1993). It is important to note that although access to sediment is critical for mangroves to survive sea-level rise, too much sediment (e.g., resulting from poor agricultural practices) can bury their pneumatophores and kill mangroves (Ellison and Stoddart 1991).

In addition to varying sediment input rates, sediment accumulation rates also differ for mangrove ecosystems worldwide. According to Ellison and Stoddart (1991), through accretion, low island mangroves can keep pace with sea-level rise of up to 1.2 mm/year, while high island mangroves can keep pace with rates of 4.5 mm/year, depending on sediment supply. As mentioned above, global projections of sea-level rise are between 1.0-8.8 mm/year, thus mangroves may not survive sea-level rise in some areas. In the low-lying island mangroves in Bermuda, the rate of sediment accretion under mangroves has been 0.8-1.1 mm per 100 years over the last 2000 years, but the present rate of sea-level rise in Bermuda exceeds 2 mm per year (Ellison 1993), clearly out-pacing the sediment accretion rate. Furthermore, the seaward margin of the mangroves has retreated and eroded significantly; 26 percent of the largest mangrove area at Hungry Bay, Bermuda, has been lost over the last century due to retreat of its seaward edge. On Kosrae Island, Micronesia, most mangrove habitats developed by accumulating mangrove peat with a gradual sea-level rise of 1.0-2.0 mm/yr (Fujimoto et al. 1996). A rapid rate of relative sea-level rise of about 10 mm/yr occurred between 4100 and 3700 B.P. and caused mangroves to retreat landward and stop accumulating peat (Fujimoto et al. 1996). Therefore, if sea-level rise exceeds 10 mm/yr, mangroves on Pacific Islands may move landward and quickly reduce in number.

Using Holocene stratigraphic records and sea-level curves for sites around the world, Ellison and Stoddart (1991) found that mangrove ecosystems can keep pace with sea-level rise of 8-9 cm per 100 years, are stressed at 9-12 cm per 100 years, and cannot adjust at rates above this level. However, Snedaker (1995) points out that over the last 147 years, sea-level rise in Florida has been about 20 cm (double the rate of collapse predicted by Ellison and Stoddart 1991), and mangrove systems in Florida have not collapsed and are even expanding in some areas. Therefore, it is critical to account for site-specific rates of change in sea level relative to the mangrove surface.

SPECIES RESPONSE TO SEA-LEVEL RISE

Individual mangrove species have varying tolerances of the period, frequency, and depth of inundation. Mangrove zones are related to shore profile, soils, and salinity, and changes in these can lead to changes in mangrove species composition. Different species may be able to move into new areas at different speeds, making some species capable of accommodating a higher sea-level rise rate than others (Semeniuk 1994). Semeniuk (1994) described how mangroves in Northwest Australia colonize new substrates that become available through erosion, inundation, and dilution of hypersaline groundwater of the salt flats. Mangrove zones displace the adjoining zone as sea level rises.

Varying tolerances of inundation and salinity may result in changes in mangrove species composition with changes in inundation and salinity due to sea level rise. For example, the SELVA-MANGRO model, an integrated landscape model, was used in Florida to predict species regeneration based on probability functions of species and community tolerance to water level and salinity (Ning et al. 2003). In persistently inundated soils, red mangrove seedlings were favored, whereas in irregularly flooded soils, white and black mangrove

seedlings were favored. This difference in seedling survival may be due more to different tolerances of inundation than to salinity. Although *Rhizophora mangle* (red mangrove), *Avicennia germinans* (black mangrove), and *Laguncularia racemosa* (white mangrove) have different salinity tolerances, their differences are only significant for salinities > 50 PSU (Menezes et al. 2003). *R. mangle* has the lowest salinity tolerance, about 70 PSU, of these three mangrove species (Chen and Twilley 1998). Menezes et al. (2003) concluded that pore water salinity had little to no influence on the tree species composition on the forest level. Therefore, the differences in seedling survival may be due to higher tolerance of inundation by *R. mangle*.

Some scientists are exploring how different functional root types of mangrove species respond to changes in elevation to determine if certain root structures may be more or less vulnerable to sea-level rise (Vicente et al. 1989; Krauss et al. 2003). In the Caribbean, Vicente et al. (1989) noted that prop roots of *Rhizophora mangle* stand higher above mean sea level than the aerial roots of *Avicennia germinans* which protrude only slightly out of the mud. These authors suggest that rapid sea-level rise may lead to local extinctions of *A. germinans* but have an insignificant effect on *R. mangle*. Ellison and Stoddart's (1991) work in Tonga also suggests that *Rhizophora* communities are better positioned to survive rising sea level due to higher peat accumulation rates beneath *Rhizophora* (5.3 mm/year) than *Bruguiera* and *Excoecaria* (2.6 mm/year).

Krauss et al. (2003) compared the vertical accretion rates and elevation change in mangrove forests in Micronesia with three different functional root types —prop roots in *Rhizophora* spp., root knees in *Bruguiera gymnorrhiza*, and pneumatophores in *Sonneratia alba*. Prop roots trapped more sediment than either pneumatophores or bare soil control sites. However, when erosion and shallow subsidence were factored into the elevation, bare

soil control sites or pneumatophores show the highest relative rates of positive elevation change. Therefore, these authors conclude that aboveground analysis of root area or belowground fine root density cannot be used to determine rates of vertical accretion or elevation change.

Appendix 2:

Summary of papers that address climate related impacts on mangroves

Temperature	Moore et al. 1972, Canoy 1975, Chapman 1977, Clough et al. 1982, Andrews et al. 1984, Burchett et al. 1984, Zhang and Lin 1984, Saenger and Moverly 1985, Hutchings and Saenger 1987, Woodroffe and Grindrod 1991, Clough 1992, UNESCO 1992, Pernetta 1993, UNEP 1994, Edwards 1995, Field 1995, Snedaker 1995, Li and Lee 1997, Ellison 2000, Burns 2001, Ellison 2005
CO₂	Ball and Munns 1992, Twilley et al. 1992, Ong 1993, UNEP 1994, Ellison and Farnsworth 1996, Farnsworth et al. 1996, Ball et al. 1997, Ayukai 1998, Snedaker and Araújo 1998, Houghton et al. 2001, Ong 2002, Chmura et al. 2003, Ong and Khoon 2003
Sea level	Hendry and Digerfeldt 1989, Vicente et al. 1989, Woodroffe 1990, Ellison and Stoddart 1991, Belperio 1993, Ellison 1993, Pernetta 1993, Semeniuk 1994, Parkinson et al. 1994, UNEP 1994, Field 1995, Snedaker 1995, Woodroffe 1995, Blasco et al. 1996, Fujimoto et al. 1996, IPCC 1997, Alongi 1998, Jones 2002, Krauss et al. 2003, Manson et al. 2003
Frequency and intensity of tropical storms	Naidoo 1983, Jimenez et al. 1985, Rey et al. 1990, Smith et al. 1994, Armentano et al. 1995, Baldwin et al. 1995, Field 1995, Roth 1997, Ellison 2000, Cahoon and Hensel 2002, Cahoon et al. 2003, Ning et al. 2003, Anthony 2004, Ellison 2004, Lollar 2004, Walsh et al. 2004, Erfteimeijer and Hamerlynck 2005
Precipitation	Burchett et al. 1984; Clough 1984, Field 1995, Snedaker 1995, Campbell 1996, Knutson and Tuleya 1999, Ellison 2000, 2004, Walsh and Ryan 2000, Drexler and Ewel 2001, Harty 2004, Erfteimeijer and Hamerlynck 2005

Appendix 3:

Mangrove mapping tools

Aerial photography and remote sensing are important tools for mangrove mapping. Field surveys in mangroves can be difficult to carry out, thus aerial photography and remote sensing provide a convenient way to collect data. Detailed classification maps are necessary to develop a baseline of mangrove areal extent, forest health, species composition, and change over time. This baseline information is useful for evaluating the impacts of climate change and for developing a habitat classification to ensure representation and replication of the full range of mangrove habitats. For a detailed explanation of the pros and cons of various remote sensing technologies for mangrove mapping, see Green et al. (2000), for an overview of publications that address mangrove mapping methods, see Appendix 4, and for low-tech approaches to surveying mangroves, see English et al. (1997).

MAPPING MANGROVE TYPES AND ZONATION

Aerial photos are able to provide higher resolution data than most remotely sensed data (Green et al. 2000; Manson et al. 2001), and they can provide detailed information about the spatial distribution of vegetation classes in relation to topographic and hydrographic features (Sulong et al. 2002; Verheyden et al. 2002). Hyperspectral sensors, such as the Compact Airborne Spectrographic Imager (CASI), can also be used to distinguish between different mangrove community types and can map these with precision (Aschenbacher et al. 1995; Green et al. 1998; Rasolofoharinoro et al. 1998; Sulong et al. 2002; Held et al. 2003; Hirano et al. 2003). Radar has been combined with hyperspectral sensors to provide general structural information related to mangrove zonation (Held

et al. 2003), to estimate the approximate age of *Rhizophora* stands, and to identify the presence of clear-cut areas or abandoned paddy fields (Aschbacher et al. 1995).

MAPPING MANGROVES AT THE SPECIES LEVEL

High resolution aerial photos can be used to map mangroves at the species scale, making them extremely useful for detailed habitat classifications (Satyanarayana et al. 2001). Although remote sensing tools are used successfully to map mangroves at the regional scale, their lack of spectral detail prevents them from being used at a species scale. To map mangroves at the species level, remote sensing tools require new sensors with high spatial and spectral details (Gao 1999; Green et al. 2000). Vaiphasa (2006) explored the use of remote sensing to map mangroves at the species level by using narrow-band hyperspectral data and the integration of ecological knowledge of mangrove-environment relationships into the mapping process. Vaiphasa (2006) concluded that in areas dominated by *Rhizophoraceae*, using spectral information alone was not enough to determine species. Vaiphasa (2006) integrated ecological data, specifically soil pH, into mangrove mapping to overcome the spectral confusion of the hyperspectral data. Combining the ecological data with the hyperspectral data increased the mapping accuracy from 76-88 percent. Some species are still not clearly differentiated (e.g., *Rhizophora mucronata* and *Sonneratia caseolaris*) even with the integration of soil pH, thus it may be necessary to incorporate more ecological data such as leaf texture from aerial photos, LIDAR-derived elevation maps, and inundation frequency maps produced by incorporating elevation maps with automatic tidal records (Vaiphasa 2006).

MAPPING MANGROVE AREA

Remote sensing data with spatial resolution of 30 m or less (Landsat ETM, SPOT HRVIR, IRS) can provide accurate estimates of mangrove area which does not differ significantly from higher resolution data (e.g., aerial photographs, CASI) (Manson et al. 2003). However, Manson et al. (2001) found that in areas where mangroves form very narrow fringes, Landsat TM underestimated their linear extent. Although CASI is more expensive and the processing time is longer than SPOT XS or Landsat TM, SPOT XS and Landsat images cover a larger area than CASI (10^4 or 10^5 as large), thus accuracy should be measured against coverage and cost (Green et al. 2000).

MAPPING MANGROVE CHANGE OVER TIME

Currently, remote sensing is the only existing technology that can be used to assess mangrove change over large areas (Green et al. 2000; Held et al. 2003; Manson et al. 2003). Multispectral sensors on satellite platforms (e.g., synthetic aperture radar (SAR), Landsat TM, and SPOT XS) are used for tracking changes in the mangrove ecosystem (Vaiphasa 2006).

MEASURING LEAF AREA INDEX

Optical satellite sensors including Landsat Thematic Mapper (TM), SPOT XS, CASI, and IKONOS can be used to estimate leaf area index (LAI) and percent canopy closure (Green et al. 1998; Kovaces et al 2005). LAI is measured to predict growth and yield, to monitor change in canopy structure caused by climate change and pollution, and has been identified as a good measure of mangrove productivity (Green et al. 2000; Kovacs et al. 2005). CASI provides excellent spatial resolution and is more accurate and more precise at measuring mangrove leaf area index (LAI) than satellite sensors such as Landsat TM and SPOT XS.

Appendix 4:

Overview of publications addressing mangrove mapping methods and overall accuracy

Method	Analysis	Accuracy	References
<i>Landsat Thematic Mapper (TM)</i>	Detecting edges of fragmented mangroves	Overall classification = 80.52 percent	Syed et al. 2001
<i>Landsat Multispectral Scanner (MSS) and TM</i>	Detecting changes in landscape using six land-use classes as indicators of landscape condition	Overall accuracy = 70 percent	Berlanga-Robles and Ruiz-Luna 2002
<i>Landsat TM</i>	Leaf area index and Canopy closure	71 percent and 65 percent, respectively	Green et al. 1998
<i>Landsat TM</i>	Mapping mangrove forests with four mangrove forest classes (homogeneous <i>Rhizophora</i> , homogeneous <i>Nypa</i> , mixed dense and mixed open mangrove forest)	68.6 percent, low accuracy partly attributed to misclassifications due to cloud cover	Aschbacher et al. 1995
<i>Landsat TM</i>	Classification of mangroves – seven vegetation classes identified	87.8 percent accuracy	Sulong et al. 2002
<i>SPOT XS</i>	Leaf area index and Canopy closure	88 percent and 76 percent, respectively	Green et al. 1998
<i>SPOT HRV images (SPOT 1 and 2) - combined with field surveys and aerial coverage (1:40 000), topographic and geological maps</i>	Classification of mangrove types, including degradation stages and prograding classes, and parameters such as density, phenology, and mangrove zonation were identified	N/A	Rasolofoharino et al. 1998
<i>Spot HRV</i>	Mapping mangrove forests with four mangrove forest classes	84.8 percent, cloud free	Aschbacher et al. 1995
<i>Compact Airborne Spectrographic Imager (CASI) with linear regression models –values of LAI predicted from normalized difference vegetation index (NDVI)</i>	Identified six mangrove classes Leaf area index and percent canopy closure	78.2 percent 94 percent for LAI and 80 percent for canopy closure	Green et al. 1998
<i>IKONOS 1-m panchromatic and 4-m multispectral images, using hybrid classification that integrates pixel and object-based methods</i>	Map different cover types and mangrove forest species composition	91.4 percent	Wang et al. 2004
<i>combined optical and radar (CASI and AIRSAR, airborne NASA's polarimetric radar)</i>	Classifying mangroves and associated non-mangroves into their species-complexes	75–80 percent	Held et al. 2003
<i>IKONOS and in situ LAI-2000 sensor data</i>	Estimated LAI at the species level	N/A	Kovacs et al. 2005
<i>Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)</i>	Mangrove classification – differentiated between red, black, and white mangrove communities and detected lather leaf, an invasive exotic species	73.5 - 95.7 percent for classification of mangrove tree species, but low classification accuracy of mangrove scrub (40 - 48 percent)	Hirano et al. 2003

RADAR

Method	Analysis	Accuracy	References
JERS-SAR(radar)	Detecting edges of fragmented mangroves	Overall classification = 85.3 percent; per class accuracy of 86.49 percent	Syed et al. 2001
Synthetic aperture radar (SAR) - combined ERS-1 and JERS-1 image data	Classification of mangrove types	52.1 percent	Aschbacher et al. 1995
Combination of JERS-1 SAR and ERS-1 SAR, with SPOT HRV, Landsat TM, and MOS-1 MESSR	Approximate age of Rhizophora stands and the presence of clear-cut areas or abandoned paddy fields can be identified	N/A	Aschbacher et al. 1995

AERIAL PHOTOGRAPHY

Method	Analysis	Accuracy	References
Visible and infrared photographic cameras (1 : 5000 aerial photographs)	Classification of mangroves – fourteen vegetation classes identified	91.2 percent accuracy	Sulong et al. 2002
Visible and infrared photographic cameras	Good for genus-based vegetation maps, but not for calculating density estimations	N/A	Verheyden et al. 2002

Appendix 5:

Mangrove Types

Lugo and Snedaker (1974) identified six physiographic types of mangrove stands: riverine mangroves, fringe mangroves, basin mangroves, overwash mangroves, scrub mangroves, and hammocks.

Riverine mangroves occur along rivers and streams and are flooded by daily tides. They occur on seasonal floodplains in areas where natural patterns of freshwater discharge remain intact with an alternating cycle of high runoff/low salinity followed by low runoff/high salinity (Gilmore and Snedaker 1993). Riverine mangroves are the most productive of mangrove communities because of the high nutrient concentrations associated with sediment trapping (Ewel et al. 1998).

Fringe mangroves occur along protected coastlines and islands and the exposed open waters of bays and lagoons. They are periodically flooded by tides and are sensitive to erosion. They often have well developed root systems and are important for protecting coastlines.

Basin forests are located inland in depressions channeling terrestrial runoff toward the coast. They are irregularly flushed by tides and are sensitive to flooding. They often serve as nutrient sinks for both natural and anthropogenically enhanced ecosystem processes and are often important sources of wood products (Ewel et al. 1998).

Overwash mangroves are subtidal to intertidal marine-dominated systems that are often located on isolated islands. They are typically inundated on each tidal cycle. Their productivity is similar to fringe mangroves.

Scrub mangroves are commonly found in extreme environments. Height is often limited and nutrients and freshwater may be limiting factors that affect growth. Tidal inundation is infrequent.

Hammock mangroves occur on slightly raised ground caused by the accumulation of organic peat over a depression. They experience infrequent tidal flushing.

In the New World, these mangrove types have been consolidated into three categories: riverine, fringing (including overwash), and basin (including dwarf and hammock) (Cintron et al. 1985).

Woodroffe (1990) divided mangroves into three types based on dominant physical processes: river-dominated (sediment brought in by rivers), tide-dominated (sediment brought in by tides), and carbonate settings (sediment is largely produced in situ, either as reef growth, calcareous sediment, or mangrove peat). More recent classification systems have been based on nutrient limitation (Feller 1995) or energy regimes (Twilley 1995).



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