

# Climate Change Vulnerability Assessment and Adaptation Planning for Mangrove Systems

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*with support from*



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We dedicate this book to *Tabé Tanjong*, who served as the initial coordinator of the WWF mangrove adaptation project in Cameroon. More broadly, he played a key role in developing WWF's conservation and climate change work in Cameroon. His untimely death was a great loss for the project and for his colleagues, family and friends.

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*Cover Photo:* WWF-Brazil/Adriano Gambarini

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# Foreword

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The world's mangrove forests are an amazing example of natural adaptation to a difficult environment. The distinctive aerial roots of mangroves help the trees flourish in a salty environment and act as nurseries for crabs, other invertebrate species and fish. Mangrove forests also provide food, fuel and other services to human communities, as well as serving as an important and effective buffer against coastal storms and floods.

Yet more than 50 percent of the world's mangroves have been destroyed during the last two decades – removed for aquaculture, agriculture and tourism development; stripped by unsustainable fishing and harvesting of wood; and choked by upstream pollution. Less than 1 percent of the world's remaining mangrove forests are adequately protected. The effects of climate change, particularly sea level rise, are expected to increase the pressure on many of the world's mangroves – which heightens the urgent need to improve their management and protection.

In 2009, with support from the Global Environment Facility (GEF), the United Nations Environment Programme (UNEP) and the Hewlett-Packard Company, World Wildlife Fund (WWF) launched an innovative project to better understand and promote coastal resilience to climate change. WWF offices in Cameroon, Tanzania and Fiji worked closely with a host of local partners, from government agencies to local communities to research institutions, to better understand how climate change will affect mangrove ecosystems (and associated coral reefs and sea grass beds) and to identify which actions can help reduce vulnerability to those impacts.

The project's primary goal was to develop a general methodology for assessing the vulnerability of mangrove ecosystems to climate change that could be used globally and to test strategies that would help those forests (and the people living around them) better adapt to climate change impacts in the future.

This manual is a key result of this multi-year, multi-country, multi-partner project. It brings together a wealth of on-the-ground experience and scientific knowledge that can help conservation practitioners, protected area managers and other stakeholders who are responsible for managing and protecting the world's mangrove forests. It walks readers through a set of eight methods for assessing climate change vulnerability in those ecosystems and offers a range of lessons and examples that will be useful for adaptation planning.

While some excellent materials for vulnerability assessment and adaptation planning have appeared in recent years, few practical guides geared towards a specific ecosystem type have become widely available in a user-friendly format oriented towards conservation practitioners in developing countries. This manual was explicitly designed to be both scientifically rigorous and extremely practical. We hope that it will be a useful tool in your efforts to help the world's mangrove ecosystems meet the challenges of thriving in a dynamic climate.



Ginette Hemley

Senior Vice President, Conservation  
Strategy and Science, WWF-US



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Photo: Jason Rubens

# Executive Summary

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## Why this manual?

Mangroves are important coastal resources that act as a protective buffer to wind and wave energy and improve near-shore water quality. Mangroves provide a major carbon sink as well as wood supplies, and sustain fishery resources that provide many coastal communities with a primary source of their daily protein intake. Mangroves are, however, one of the most threatened ecosystems in the world, with many countries having lost 50 percent of their mangroves to conversion and degradation in the last 20 years.

Mangrove ecosystems are also sensitive to climate change impacts, particularly to associated relative sea level rise. Intertidal mangroves are most extensively developed on sedimentary shorelines where the rate of mud accretion determines their ability to keep up with sea level rise. The Intergovernmental Panel on Climate Change (IPCC) 4th Assessment projected a global sea level rise of up to 0.59 m by 2099, and subsequent authorities have projected up to 1 m or more. Mangrove accretion rates are usually less than these projected rates of sea level rise, resulting in dieback at the seaward edge and inland migration. Mangrove productivity and biodiversity are also vulnerable to rainfall variability or reduction.

To date, there has been limited development of climate change vulnerability assessment methods and adaptation actions that are specific to mangroves. Procedures are needed to assess the vulnerability of mangrove systems to climate change impacts; to plan actions that help those systems adapt to those impacts; and to support adaptation efforts by mangrove-dependent communities.

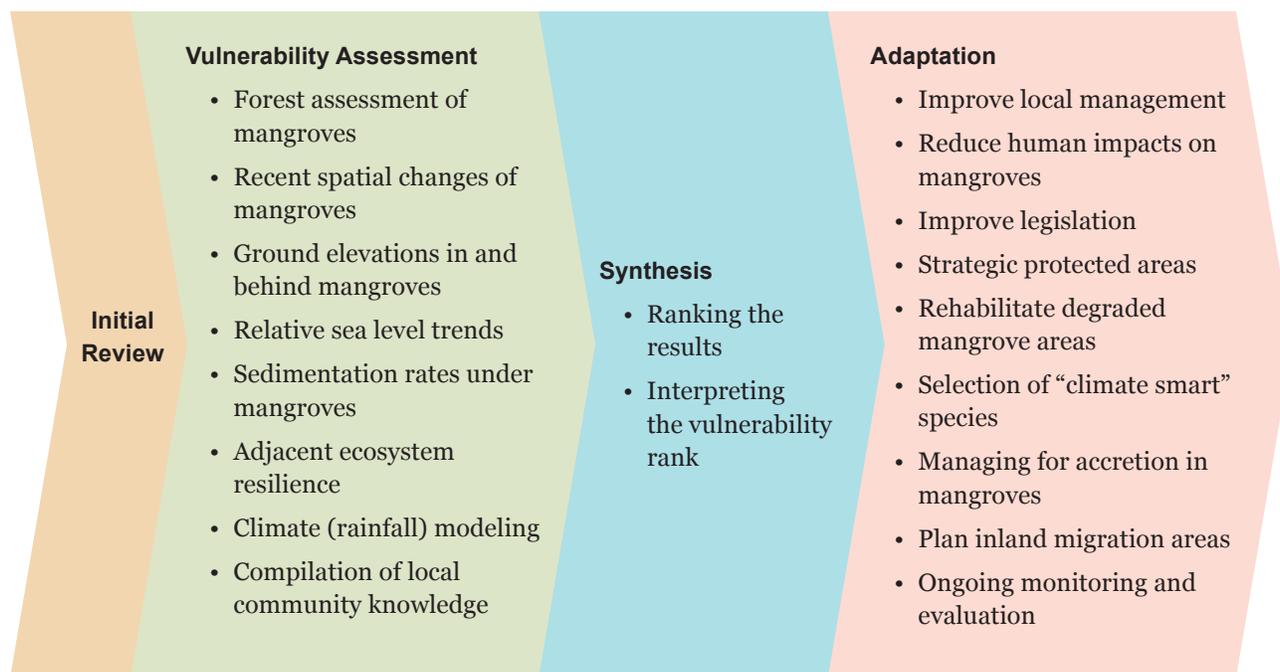
## Who is this manual for?

This methods manual is intended for use by conservation practitioners and mangrove managers to carry out an assessment of mangrove vulnerability to climate change, leading to informed and effective adaptation planning. The manual's objectives are to describe methodologies and give examples for carrying out such a vulnerability assessment; and to demonstrate how the results can be analyzed and applied to prioritize adaptation actions.

## How was this manual developed?

Although climate change impacts on mangroves are well known, vulnerability assessment procedures and adaptation options to date have been speculative. With support from the Global Environment Facility (GEF) and United Nations Environment Programme (UNEP) and in close collaboration with a range of institutional partners, stakeholders and local communities, the World Wildlife Fund (WWF) has tested mangrove vulnerability assessment methodologies and adaptation strategies in three countries: Cameroon, Tanzania and Fiji.

These pilot projects involved interdisciplinary data collection using both high- and low-technology methods, and analysis of how each method helped to understand the vulnerability of a particular mangrove ecosystem. Working with local communities, WWF offices also used these vulnerability assessment results to identify and test a range of adaptation options. The findings of these pilots guided the development of this generalized methodology.



## How to do vulnerability assessments

Vulnerability is a combination of exposure, sensitivity and adaptive capacity factors. In mangrove ecosystems, tidal range, relative sea level trends, sediment supply and drier climate are all exposure factors, while sensitivity factors include forest condition and growth, seaward edge retreat, reduction in mangrove area, elevations within mangroves, sedimentation rates, adjacent ecosystem resilience and strength of protection legislation. Adaptive capacity factors include available migration areas inland from mangroves, community management capacity and degree of stakeholder involvement in mangrove management.

Local communities in and around a given mangrove area and stakeholders involved with mangrove resource use and management are integral to the development of a vulnerability assessment and adaptation plan. They must be informed, involved and integrated into the assessment and planning stages.

Prefaced by a desktop review of existing information that guides the other components, this mangrove climate change vulnerability assessment methodology has eight components:

- forest assessment of mangroves
- recent spatial changes of mangroves
- ground elevations in and behind mangroves
- relative sea level trends
- sedimentation rates under mangroves
- adjacent ecosystem resilience
- climate (rainfall) modeling
- compilation of local community knowledge

This manual provides guidance for each component on what it is, why to do it, how to collect data, how to analyze results, how to interpret vulnerability and what are the component’s strengths and limitations. Exposure factors of geomorphic setting and tidal range are incorporated. Case studies from the WWF pilot sites are used to illustrate these methods throughout the manual.

Guidance is also provided for each component on the scale of expertise required, the time required, its relative cost and its relative usefulness for the next stage of synthesizing into a vulnerability assessment to guide adaptation planning. It may not be necessary to carry out all components because of existing information obtained through the desktop review. Criteria are given to help a reader decide which components should be priorities.

## How to synthesize the data to guide adaptation planning

The results from each component are ranked on a scale from one to five and then combined into an integrative tool to assess the vulnerability of the mangrove area. The most critical components of the vulnerability assessment are those that assess the exposure factors of relative sea level rise and sediment supply, and the sensitivity factors of forest condition, recent spatial change and sedimentation rates. These identify the tipping points for the mangrove area, whereas the other results may help but are less critical. Also important is local community knowledge, which is an indicator of social vulnerability rather than a direct measure of ecosystem vulnerability.

This vulnerability ranking facilitates the identification of adaptation actions that reduce the identified vulnerabilities and increase resilience. There are three categories of actions: reduction of existing (non-climate) threats, direct adaptation actions and ongoing monitoring (which is of great importance). These actions include

- improving local management
- improving legislation
- establishing strategic protected areas
- rehabilitating degraded mangrove areas
- selecting “climate-smart” species
- managing for accretion in mangroves
- proactive planning for changed conditions
- continued monitoring of mangrove extent and condition
- continued monitoring of mangrove sedimentation rates

The vulnerability assessment ranking helps conservation practitioners prioritize, among possible adaptation actions, those that will be of the greatest benefit in a particular site. These actions are what can be done to reduce the vulnerability of the mangrove system to the impacts of sea level rise, in particular, and to increase the adaptive capacity of people living near the mangroves to assist in this process.

## Overall analysis

The synthesis of results from the different vulnerability assessment components helps to identify the most appropriate adaptation actions. The methods are applicable to mangroves in different geomorphic settings (riverine, deltaic, fringe, lagoonal and low islands); and guidance is given on the different sensitivities of each type. Through the case study pilots, WWF has developed this generalized methodology for assessing vulnerability in mangrove ecosystems and developing adaptation strategies to assist conservation practitioners around the world. We hope that this manual provides useful guidance for this critical task.

We welcome feedback and the sharing of experiences, which can be sent directly to the author:  
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Photo: Joanna Ellison



Photo: Monifa Fiu

# 1.0 Mangroves: Values, Status and Threats

Mangrove forests occur most extensively on sheltered, sedimentary shorelines of the tropics in intertidal situations such as deltas and estuaries. Mangroves have special adaptations for a wet, saline environment such as aerial roots, which makes them unique from other trees. While the center of mangrove biodiversity is Southeast Asia, common genera, such as *Rhizophora*, *Bruguiera* and *Avicennia*, occur across most of the tropics (Figure 1).

## 1.1 Mangrove values

Mangroves play an integral role in coastal ecosystems at the interface between terrestrial, freshwater and marine systems. Mangroves afford protection to both terrestrial and estuarine systems from high-energy marine processes, preventing erosion and buffering coastal communities from tropical cyclonic storms. The forests also act to filter runoff water and so protect offshore sea grass beds and coral reefs from

deposition of suspended matter discharged by rivers. Mangrove ecosystems are a significant carbon sink in terms of forest biomass as well as organic sediment accumulation (Donato et al., 2011; Bouillon, 2011). For centuries, mangroves have provided a wide range of products for coastal communities, such as timber and fuelwood and bioactive compounds for tanning and medicinal purposes (MacNae, 1968; Spalding et al., 2010). These values are illustrated in Figure 2.

One of the most important values of mangroves to people is their support of ecologically and economically important fish species (Robertson & Duke, 1990; Kimani et al., 1996; Baran & Hambrey, 1999; Mumby et al., 2004; Chitaro et al., 2005). The ecosystem is known to act as a nursery site for many fish and crustacean species important for both commercial and subsistence purposes. Many studies have shown that mangroves harbor high densities of juvenile reef fish (Ley & McIvor, 2002) and provide an intermediate nursery stage between sea grass beds and patch reefs (Mumby et al., 2004). Juvenile survivorship

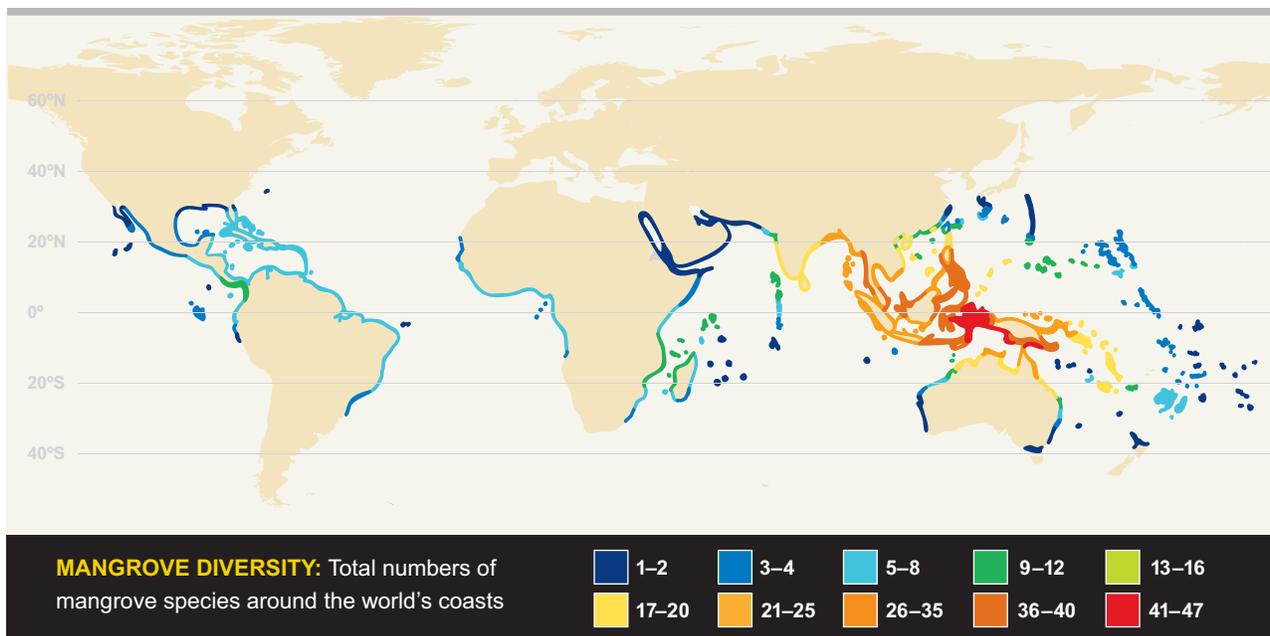
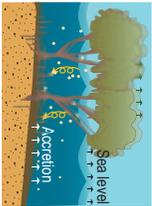


Figure 1: Native distributions of mangrove species.



# What are the benefits of healthy mangroves?

## 1. Mangroves build the land and hold and protect it from erosion



As sea level rises, mangroves build up soil, keeping pace with sea level rise and protecting the land from erosion.

Mangroves are a dynamic buffer between land and sea, clinging to soil and protecting it from wave energy.



Crabs feed on fallen mangrove leaves, pulling them into their holes. Urethan leaf matter and crab feces all help to build up the soil.



Mangrove soil is formed from trapped sand and mud, and from small pieces of broken-down plant matter.



When waves reach the mangroves, their energy is reduced, helping to prevent erosion.



Broken off seagrass, sand and shells are deposited onto mangroves during storms.

## 3. Mangroves are productive in ways that benefit people and the environment



Mangroves are a primary producer of plant material that feeds sea life.

Mangroves are important habitat for resident and migratory birds.



Mangroves provide a living place for many plants and animals that are in turn eaten by others including commercial species.



Juvenile fish feed and hide in mangroves. Decomposing plant matter (detritus) from mangrove leaves feeds phytoplankton that are major primary producers in mangrove ecosystems.



Mangroves protect coastal communities from storm waves and tsunamis by reducing the energy of these destructive waves as they cross the shoreline.

## 2. Mangroves help to keep the water clean and clear



Mangroves help to keep the water clear by trapping fine particles of mud. These particles also help to build up the soil.



Mangroves "filter" water running off the land. They trap dirt, making the water less murky and removing excess nutrients and chemicals that would pollute offshore waters and coral reefs.



As mangroves build soil partly by accumulating organic matter from the breakdown of plants, carbon is captured and stored, helping to reduce greenhouse gases.



Healthy, productive mangroves support traditional small-scale fisheries, providing local villages with a rich source of protein.

**LEGEND**

Rainforest	Mangrove Trees	<i>Bruguiera</i>	<i>Centropus</i>	<i>Rhizophora</i>	<i>Avicennia</i>	mangrove leaf	Seagrass	Mussels	Diverse crabs and shrimps	Mudskipper	Juvenile fish	Fishes	Resident and migratory shorebirds	People
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Figure 2. Values of mangrove ecosystems.

By Jan Tilden

is enhanced in mangroves, which provide refuge from predators and offer plentiful food. Mangroves therefore strongly influence the community structure and abundance of fish in offshore waters. For example, the biomass of several commercially important species is more than doubled when the adult habitat is connected to mangroves (Mumby et al., 2004).

Mangroves also have an important role in protecting coasts during storm and tsunami events, both by frictional reduction of wave energy and by promoting sedimentary resilience to erosion through the root mat (Massel et al., 1999; Dahdouh-Guebas et al., 2005; Danielsen et al., 2005; Katharesan & Rajendran, 2005; Hirashi, 2008). Studies following the 2004 tsunami found that, in some places, human deaths and loss of property were reduced by the presence of coastal vegetation shielding coastal villages (Dahdouh-Guebas et al., 2005; Katharesan & Rajendran, 2005; Walters et al., 2008). Reduction of wave height and energy is influenced by the structure of the mangrove forest and the type of aerial root systems.

## 1.2 Present status and threats

Despite these values, many mangrove systems have been degraded and destroyed throughout their ranges (Valiela et al., 2001; Food and Agriculture Organization of the United Nations, 2003; Spalding et al., 2010; Giri et al., 2011), and as a result, many coastal towns and communities are losing resources on which they depend. Mangrove area worldwide fell from over 200,000 km<sup>2</sup> before 1950 to 188,000 km<sup>2</sup> in 1980, and to below 150,000 km<sup>2</sup> by the end of 2000 (FAO, 2003), with the vast majority of that loss after 1980. Asia has suffered the highest losses (FAO, 2007); and because data used in these assessments preceded the 2004 Asian tsunami, the losses were due to human impacts (Valiela et al., 2001; Manhas et al., 2006; Duke et al., 2007). A recent area reassessment put the 2000 global extent of mangroves at only 137,760 km<sup>2</sup> (Giri et al., 2011). The implied rates of loss are faster than of tropical rainforests or coral reefs (Duke et al., 2007), but generally receive far less attention (FAO, 2003). The rate of mangrove deforestation was

1.7 percent a year from 1980 to 1990 and 1.0 percent a year from 1990 to 2000 (FAO, 2003), slowing to 0.66 percent in the five years before 2005 (FAO, 2007; Spalding et al., 2010), although 13 countries or territories do not have mangrove area data or have only a single estimate (FAO, 2007).

The following direct human impacts on mangroves lead to habitat degradation and deteriorating water quality:

- conversion to aquaculture
- conversion to agriculture
- overharvesting for timber
- unsustainable fishing and other extractive uses
- conversion to development, tourism and coastal infrastructure
- pollution

Climate change has begun to compound the effects of many of these threats, as discussed in the next section. Degradation and loss of these coastal systems due to climate change and direct human impacts negates the protection they provide during extreme events and reduces their adaptive capacity, with significant environmental, social and economic consequences for coastal communities.

## 1.3 Climate change effects on mangroves

It has been substantially demonstrated that mangroves are affected by climate change (Nicholls et al., 2007), as shown by the reviews summarized in Table 1. Temperature increases and the direct effects of CO<sub>2</sub> increases are likely to be mostly beneficial, increasing mangrove productivity and biodiversity. Rainfall changes are of greater significance to mangroves, particularly reduced rainfall, which decreases productivity and biodiversity. However, the effects of relative sea level rise are the primary impact of concern, with a number of severely detrimental effects on mangroves (Table 1).

Factor	Processes affected	Impacts	References
Rising sea level	<ul style="list-style-type: none"> <li>- Forest health</li> <li>- Forest productivity</li> <li>- Recruitment</li> <li>- Inundation period</li> <li>- Sedimentation rates</li> </ul>	<ul style="list-style-type: none"> <li>- Forest mortality, dieback from the seaward edge</li> <li>- Migration landward, but dependent on sediment inputs, topography and human modifications</li> </ul>	Ellison, 1993, 2005; Semeniuk, 1994; Cahoon et al., 2006; Gilman et al., 2008; Soares, 2009
Extreme storms	<ul style="list-style-type: none"> <li>- Forest productivity</li> <li>- Recruitment</li> <li>- Sedimentation rates</li> </ul>	<ul style="list-style-type: none"> <li>- Forests damaged or destroyed</li> <li>- Ground elevation change</li> <li>- Erosion or sediment smothering</li> </ul>	Jaffar, 1992; Dahdouh-Guebas et al., 2005; Alongi, 2008; Yanagisawa et al., 2009
Increased waves and wind	<ul style="list-style-type: none"> <li>- Sedimentation rates</li> <li>- Recruitment</li> </ul>	<ul style="list-style-type: none"> <li>- Changes in forest coverage, depending on whether coasts are accreting or eroding</li> </ul>	Semeniuk, 1994
Increased air and sea temperature	<ul style="list-style-type: none"> <li>- Respiration</li> <li>- Photosynthesis</li> <li>- Forest productivity</li> </ul>	<ul style="list-style-type: none"> <li>- Reduced productivity at low latitudes and increased winter productivity at high latitudes</li> </ul>	Clough & Sim, 1989; Cheeseman et al., 1991; Cheeseman, 1994; Cheeseman et al., 1997
Enhanced CO <sub>2</sub>	<ul style="list-style-type: none"> <li>- Photosynthesis</li> <li>- Respiration</li> <li>- Biomass allocation</li> <li>- Forest productivity</li> </ul>	<ul style="list-style-type: none"> <li>- Increased productivity, subject to limiting factors of salinity, humidity and nutrients</li> <li>- Soil elevation gain</li> </ul>	Snedaker, 1995; Farnsworth et al., 1996; Ball et al., 1997; Langley et al., 2009
UV-B radiation	<ul style="list-style-type: none"> <li>- Morphology</li> <li>- Photosynthesis</li> <li>- Forest productivity</li> </ul>	<ul style="list-style-type: none"> <li>- Minor</li> </ul>	Lovelock et al., 1992; Day & Neale, 2002; Caldwell et al., 2003
Increased rainfall	<ul style="list-style-type: none"> <li>- Sediment inputs</li> <li>- Ground water</li> <li>- Salinity</li> <li>- Productivity</li> </ul>	<ul style="list-style-type: none"> <li>- Increased sediments and maintenance of surface elevation</li> <li>- Increased ground water</li> <li>- Increased diversity</li> <li>- Increased productivity</li> <li>- Increased recruitment</li> </ul>	Smith & Duke, 1987; Rogers et al., 2005; Whelan et al., 2005; Krauss et al., 2003
Reduced rainfall	<ul style="list-style-type: none"> <li>- Sediment inputs</li> <li>- Ground water</li> <li>- Salinity</li> </ul>	<ul style="list-style-type: none"> <li>- Reduced sediments and relative subsidence</li> <li>- Migration landward</li> <li>- Reduced ground water</li> <li>- Reduced photosynthesis</li> <li>- Reduced productivity</li> <li>- Species turnover</li> <li>- Reduced diversity</li> </ul>	Rogers et al., 2005; Rogers et al., 2005; Whelan et al., 2005; Smith & Duke, 1987
Reduced humidity	<ul style="list-style-type: none"> <li>- Photosynthesis</li> <li>- Forest productivity</li> </ul>	<ul style="list-style-type: none"> <li>- Reduced productivity</li> <li>- Species turnover</li> <li>- Reduced diversity</li> </ul>	Clough & Sim, 1989; Cheeseman et al., 1991; Cheeseman, 1994; Ball et al., 1997

**Table 1. Predicted effects of climate change factors on mangroves with key references (adapted from Lovelock & Ellison, 2007).**

Type Attributes	River-dominated	Tide-dominated	Wave-dominated	River- and wave-dominated	Low island
<b>Geomorphic setting</b>	Deltaic distributaries	Estuarine with elongated islands	Barrier islands/spits and lagoons	Distributaries and lagoons	Marine-dominated
<b>Sediment source</b>	Allochthonous	Allochthonous	Autochthonous	Allochthonous	Autochthonous
<b>Tidal range</b>	Low	High	Any	Any	Low
<b>Mangrove locations</b>	Seaward edge and distributaries	Tidal creeks and islands	Inside lagoons	Low-energy distributaries and lagoons	Fringing or basin
<b>Dominant process</b>	Freshwater discharge	Tidal currents	Wave energy	Wave energy and freshwater discharge	Sea level
<b>Examples</b>	Mississippi; Ganges-Brahmaputra; Rufiji, Tanzania	Ord, Australia; Fly, Papua New Guinea; Klang, Malaysia	El Salvador; Mono, Benin; Laguna de Terminos, Mexico	Grijalva, Mexico; Burdekin, Australia; Sanaga, Cameroon	Tongatapu; Kiribati; Grand Cayman; Jaluit, Marshall Islands
<b>Specific vulnerability</b>	Change in discharge and sediment supply	Increased tidal action; change in sediment budgets	Increased wave action; change in sediment budgets	Reduction in sediment supply	Low sedimentation rates

**Table 2. Mangrove geomorphic settings and their controlling attributes (adapted from Thom, 1982; and Ellison, 2009a).**

The response of mangrove habitats in different coastal locations to climate change will depend on a number of factors of coastal behavior, including tidal range, sedimentology, salinity regime, community composition and shore profile. Although they are intertidal, mangroves occur in a range of settings that may have different vulnerabilities to climate change impacts (Table 2).

*Allochthonous* means that there are external sources of sediment for the mangroves, particularly from rivers. This sediment tends to be inorganic, and mangrove systems that have such sediment supply have higher sedimentation rates, making them less vulnerable to sea level rise.

*Autochthonous* means that sediment sources are primarily organic and from *in situ* mangrove production, resulting in peaty sediment. Mangroves with such sediment supply tend to have lower sedimentation rates, making them more vulnerable to sea level rise. These factors are incorporated into the vulnerability ranking in Section 4.

Tidal range and relative sea level change are key exposure factors relating to the vulnerability of mangroves to sea level rise. For example, sea level rise will have a greater impact on intertidal systems in microtidal areas than in macrotidal areas because the tidal zone relocation will be more complete (Figure 3). Global sea level rise will also have a greater impact on areas that already suffer from relative sea level rise due to deltaic subsidence. Identification and interpretation of such vulnerabilities are the objectives of Sections 3 and 4 of this manual.

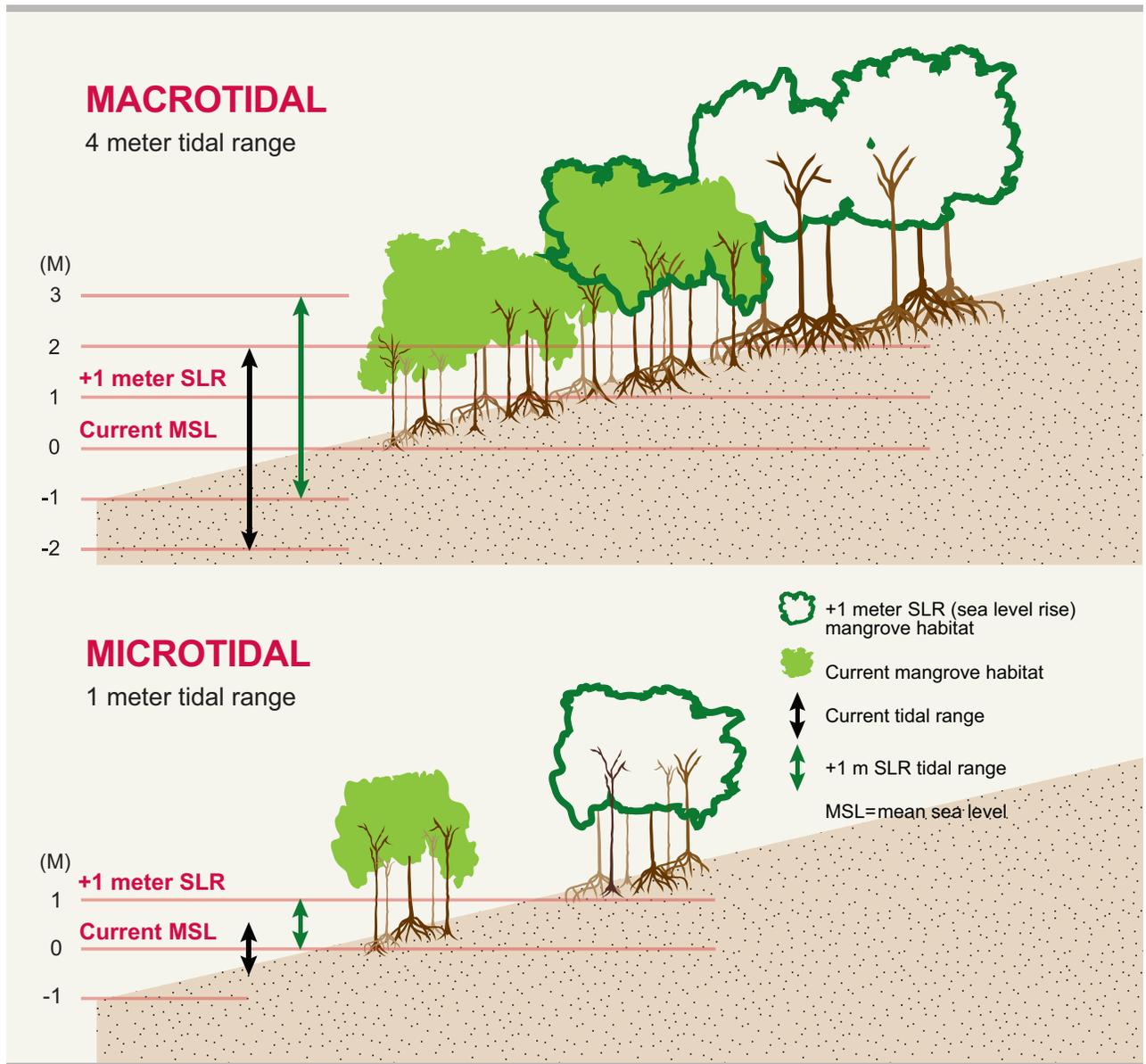


Figure 3. Extent of sea level rise displacement of macrotidal systems compared with microtidal systems.

## 2.0 Planning a Vulnerability Assessment

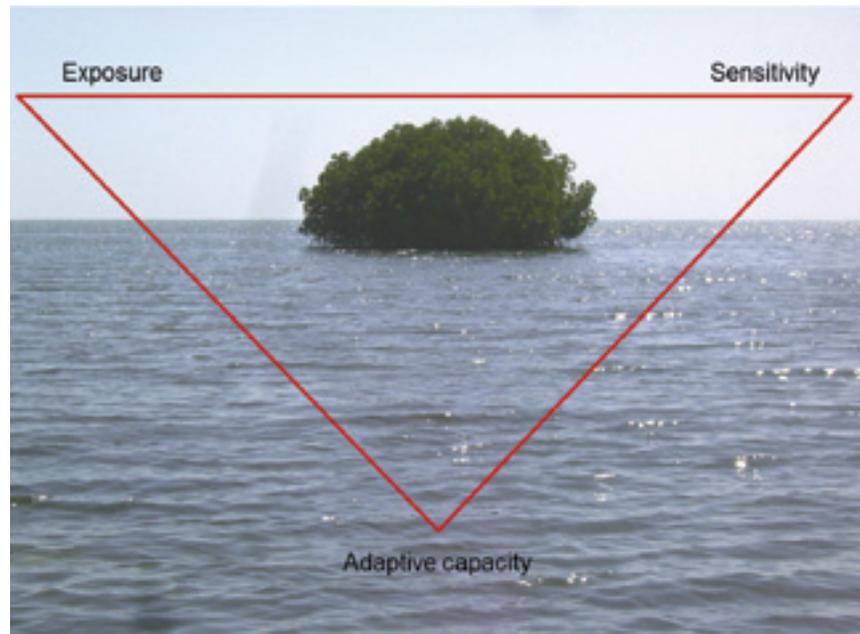
This methods manual is intended to be used by field practitioners and mangrove managers to carry out an effective assessment of mangrove vulnerability to climate change, leading to informed and effective adaptation planning. The objectives are to provide methodologies that assess different components of vulnerability and to demonstrate how results can be analyzed, compiled into an overall assessment of vulnerability and applied to make adaptation decisions.

### 2.1 Background

Vulnerability and adaptive capacity have emerged in the last decade as useful concepts for analyzing coupled human-environment response to climate change (Adger et al., 2007). An early focus was on the human or economic aspects of vulnerability and adaptation in consideration of human systems such as agriculture, public health and response to hazards (Kelly & Adger, 2000). Only recently have natural systems such as species, habitats and ecosystems been assessed for their climate change vulnerability (Zhao et al., 2007; Lovelock & Ellison, 2007; Nitschke & Innes, 2008; Glick & Stein, 2010).

Vulnerability is generally described as a function of three elements: exposure, sensitivity and adaptive capacity (Figure 4). Vulnerability is the potential to be harmed by a combination of exposure and sensitivity to stresses and is reduced by the capacity to adapt to those stresses (Adger et al., 2007; Mertz et al., 2009).

*Exposure* refers to extrinsic factors, focusing on the character, magnitude and rate of change that a species or system is likely to experience, such as rate of relative sea level rise. *Sensitivity* generally refers



**Figure 4. Vulnerability of mangroves as a combined function of exposure, sensitivity and adaptive capacity.**

to innate characteristics of a species or system and considers tolerance to changes in such factors as temperature, rainfall, humidity, seasonality or fire. In mangroves, sensitivity is shown by decline in forest condition, productivity, biodiversity, stability over time and resilience. *Adaptive capacity* refers to the ability of a species or system to accommodate or cope with climate change impacts with minimal disruption (Glick & Stein, 2010). This can be through ecosystem or species response or through human actions that reduce vulnerability to actual or expected changes in climate. Resilience is the ability to absorb and recover from the effects of disturbance, while resistance is the ability to withstand change and continue to function. Hence, adaptation includes actions to reduce vulnerability or enhance resilience (Adger et al., 2007).

There has been little development of methodologies for carrying out vulnerability assessments and planning adaptation actions that are particularly useful in mangroves or even in associated systems. There are useful reviews of mangrove vulnerability and resilience-

building based on existing impact assessment literature (McLeod & Salm, 2006; Gilman et al., 2006a; Gilman et al., 2006b; Lovelock & Ellison, 2007; Gilman et al. 2008; Gehrke et al., 2011; Waycott et al., 2011), but these do not extend into tested methods.

## 2.2 Pilot sites

With support from the Global Environment Facility (GEF) and United Nations Environment Programme (UNEP) and in close collaboration with a range of institutional partners, stakeholders and local communities, the World Wildlife Fund (WWF) tested mangrove vulnerability assessment methodologies and adaptation strategies to build and strengthen the capacity of conservation practitioners and managers. Pilot sites in three countries – Cameroon, Tanzania and Fiji (Figure 5 and Table 3) – were selected for the following reasons:

- Tropical Africa and the South Pacific are predicted to experience among the most severe consequences of global climate change (Intergovernmental Panel on Climate Change, 2007a), because of high exposure and low adaptive capacity.
- All the sites are deltaic/estuarine and so represent the most extensive types of mangroves worldwide (Giri et al., 2011).
- All the sites have six to eight mangrove species, one with Atlantic species and two with eastern Asian species (Figure 1 and Table 4).
- All the sites lack a record of relative sea level trends from either local tide gauges or proxy sea level history, which made the task more challenging but provided an opportunity to investigate alternate methods.
- All the sites have low tidal ranges, likely to be most vulnerable to sea level rise.
- Two of the sites (Tanzania and Fiji) also include island ecosystems with increased vulnerabilities to sea level rise.
- All the sites have a long history of WWF collaboration and interaction with local communities.
- All the sites are occupied by traditional cultures that are dependent on the natural resources provided by healthy coastal ecosystems.



Photo: Joanna Ellison



Photo: Joanna Ellison



Photo: Joanna Ellison

Pilot sites (from top): Cameroon, Tanzania and Fiji.



Figure 5. WWF mangrove project areas in Cameroon (1), Tanzania (2) and Fiji (3).

	Douala Estuary, Cameroon	Rufiji Delta, Tanzania	Tikina Wai, Fiji
<b>Latitude and longitude</b>	3.2°–3.6° N 9.3°–10.1° E	7.0°–9.0° S 37.0°–39.5° E	17.5°–18.1° S 177.1°–177.2° E
<b>Physical landscape</b>			
Total land area (km <sup>2</sup> )	1,600	1,200	89.6
Mangrove area (km <sup>2</sup> )	172	500	4.4
Geomorphic setting	Large river estuary	Large river delta	Small river estuary
Tidal range (m)	1.2	Offshore reefs 3.3	Offshore reefs 1.4
<b>Climate type</b>			
Precipitation patterns	Equatorial	Monsoonal	Drier leeward
Annual rainfall (mm)	4,114	1,200	1,882
Air temperatures (°C)	24.0–29.0	24.0–31.0	25.5–30.8
Relative humidity (%)	74–86	60–80	c. 70
<b>Demographics</b>			
Number of villages	20	18	6
Total population	5,600	26,583	2,026
Human population density/km <sup>2</sup>	3.5	22	23
Annual population growth (%)	2.9	2	-0.3 to 0
<b>Major economic activities</b>	Fishing and fish smoking, subsistence agriculture, palm oil and tea plantations, tourism	Rice and other farming, semi-commercial fishing including shrimp/prawns	Sugarcane farming, pine plantations, tourism, semi-commercial fishing
<b>Pilot site coordination</b>	WWF Central Africa Regional Program Office, Yaoundé	WWF Tanzania Program Office, Dar es Salaam	WWF South Pacific Program Office, Suva

Table 3. Baseline information on environmental, social and economic settings of the three pilot sites.

Genus and common name	Species	Cameroon	Tanzania	Fiji
<i>Rhizophora</i> Red mangrove	<i>Rhizophora harissonii</i>	✓		
	<i>Rhizophora racemosa</i>	✓		
	<i>Rhizophora mangle</i>	✓		
	<i>Rhizophora mucronata</i>		✓	
	<i>Rhizophora stylosa</i>			✓
	<i>Rhizophora samoensis</i>			✓
<i>Bruguiera</i> Oriental mangrove	<i>Bruguiera gymnorhiza</i>		✓	✓
<i>Avicennia</i> Black mangrove	<i>Avicennia marina</i>		✓	
	<i>Avicennia germinans</i>	✓		
<i>Heritiera</i> Looking-glass mangrove	<i>Heritiera littoralis</i>		✓	✓
<i>Excoecaria</i> Blind-your-eye mangrove	<i>Excoecaria agallocha</i>			✓
<i>Lumnitzera</i> Black mangrove	<i>Lumnitzera littorea</i>			✓
	<i>Lumnitzera racemosa</i>		✓	
<i>Conocarpus</i> Buttonwood	<i>Conocarpus erectus</i>	✓		
<i>Laguncularia</i> White mangrove	<i>Laguncularia racemosa</i>	✓		
<i>Ceriops</i> Yellow mangrove	<i>Ceriops tagal</i>		✓	
<i>Sonneratia</i> Mangrove apple	<i>Sonneratia alba</i>		✓	
<i>Xylocarpus</i> Cannonball mangrove	<i>Xylocarpus granatum</i>		✓	✓

**Table 4. Native mangrove species present at WWF mangrove project sites, Cameroon, Tanzania and Fiji.**

These pilots involved interdisciplinary data collection using high- and low-technology methods and analysis of how each method helped to identify the overall vulnerability of a particular mangrove ecosystem. Working with local communities, conservation practitioners also used the vulnerability assessment results to identify and test a range of adaptation options. The findings of these pilots guided the development of this generalized methodology.

## 2.3 Objectives of the vulnerability assessment

A vulnerability assessment (VA) begins with an examination of the mission, vision, goals and objectives of the group doing the assessment (Hansen & Hoffman, 2011). Therefore, the first activity is to clearly document why the assessment is being undertaken. What are the unanswered questions, and what is to be achieved by the assessment? Most VAs have the objective of identifying vulnerability in a given

system; and then proposing adaptation or adaptive management strategies to reduce that vulnerability.

The objectives of this manual are to describe methodologies and give case studies for a vulnerability assessment that is specific to mangrove ecosystems; and to demonstrate how the results of that assessment can be analyzed and applied to adaptation planning.

## 2.4 Overarching principles for any VA

The following six principles best guide any VA (adapted from Schroter et al., 2005):

1. The approach should be interdisciplinary to encompass the human-biophysical environment system, rather than human or environmental systems in isolation.
2. The approach should be participatory, involving stakeholders to understand their perspectives and knowledge; engaging local communities living in and adjacent to the area of interest; and including them in planned adaptation actions.

3. The study area should be a landscape/seascape unit, such as a delta, rather than an entire country. This scale should be such that exposure factors are fairly uniform within the study area.
4. The global change drivers included should be recognized as multiple and interacting with socioeconomic development and land-use changes. Ultimately, all of these drivers interact with and affect processes within the human-environment system.
5. The assessment should allow for differential adaptive capacity. Adaptation options may be constrained by inadequate resources or information or political and institutional barriers.
6. The assessment should be both historical and forward-looking. Past biophysical and social records for a particular area can show resilience or changeability, which will assist in understanding vulnerability.



Photo: Brigid Morrison

## 2.5 Community and stakeholder involvement

Involving different stakeholders, including local communities, in the vulnerability assessment and adaptation process is treated as more of an overarching or crosscutting principle (as identified in section 2.4) than a specific methodology. However, it is essential that specific steps are taken throughout the assessment to ensure that this is carried out effectively. The WWF vulnerability assessment process at the three pilot sites involved multiple stakeholder groups in each country throughout the planning and implementation stages. For instance, mangrove management usually involves different government ministries and departments, which are governed by separate pieces of legislation (Fiu et al., 2010).

Stakeholder involvement can be improved by identifying and working with existing resource management structures and processes at both national and local levels. Stakeholder workshops are useful at the beginning of a VA as a scoping and information-sharing exercise. Toward the end of the assessment, when findings are available, such workshops can contribute to these findings with respect to regional-scale planning, the improvement of policy and the identification of other relevant adaptation measures.

Stakeholder contributions are facilitated by ongoing communication through facilitator consultation, emails, meetings and sharing of reports and results. This can be assisted by the delivery of materials in suitable formats, such as local-language publications. Such a focus on engagement, as well as a specific communications plan, should permeate all of the vulnerability assessment methodologies in the following section. Some specific methodologies for the compilation of community knowledge and its use in adaptation are outlined in section 3.9.

## 3.0 Conducting a Vulnerability Assessment

Because climate change effects on mangroves may be significant and may already be occurring, mangrove management requires the development of adaptive ecosystem management strategies. The vulnerability assessment methodology outlined here is designed to identify which aspects of the mangrove system are already experiencing climate change impacts and which aspects are most vulnerable to future impacts.

Sub-section number	Vulnerability assessment component	Approach
3.1	Initial review of existing information	Desktop computer searches, stakeholder inquiries
3.2	Forest assessment of mangroves	Transect-based permanent plots and rapid assessment methods
3.3	Recent spatial changes of mangroves	Aerial photograph and satellite image analysis of change by GIS
3.4	Ground surface elevations in and behind mangroves	High-technology survey or water level correlation
3.5	Relative sea level trends	Tide gauge analysis or stratigraphy, radiocarbon dating, pollen analysis
3.6	Sedimentation rates under mangroves	Sedimentation stakes, surface elevation tables, dates on stratigraphy
3.7	Adjacent ecosystem resilience	Standard coral reef and sea grass monitoring methods
3.8	Climate (rainfall) modeling	Assessment of available projections
3.9	Compilation of local community knowledge	Facilitated workshops, structured questionnaires

**Table 5. Summary of the components of a mangrove vulnerability assessment, showing subsections of Section 3 where they are described.**

Table 5 shows the interdisciplinary combination of approaches that together form a mangrove vulnerability assessment. These methods are expanded in the following subsections as labeled in Table 5, and their interpretation is summarized in Section 4. All of the components are recommended for a complete assessment, but some are more critical than others, as rated in a table at the beginning of each subsection; and some may be partly complete, as determined by the initial desktop review.

Most of the subsections also include an example from the WWF pilot project, showing how results can be used to establish a vulnerability ranking.

In ‘How to interpret vulnerability’ portions of each component subsection, guidance is given on how to rank vulnerability using a five-point scale. The ‘How to analyze results’ and ‘How to interpret vulnerability’ discussions under each component of Section 3 can be used to determine each score.

Because vulnerability is a combination of exposure, sensitivity and adaptive capacity factors, the contribution of each component is so identified. Tidal range, relative sea level trends, sediment supply rates and precipitation change are all exposure factors, while sensitivity factors are forest condition and growth, seaward edge retreat, reduction in mangrove area, elevations within the mangroves, sedimentation rates, adjacent ecosystem resilience and strength of protection legislation. Adaptive capacity factors are availability of migration areas inland from mangroves, community management capacity and degree of stakeholder involvement in mangrove management.

To obtain an overall mangrove vulnerability assessment ranking, the scores assigned for components in Section 3 are collated into a score in Section 4. These results are then used to identify adaptation actions to reduce vulnerability in Section 5.

### 3.1 Initial desktop review of existing information

Approach	Expertise/Technology needed	Time taken	Cost	Contribution to VA
Desktop	Some	Some	Low	Rather high

**Key to scales:** 1–Low; 2–Some; 3–Moderate; 4–Rather high; 5–High

It is important and cost-effective to carry out an initial desktop compilation and assessment of existing data that may be relevant to the site or the VA approaches described in Table 5. This desktop review may reduce the need for additional data collection or enhance the project by contributing longer-term trend data. Here are some examples of sources to review, linked to the relevant subsections that follow:

- Mangrove baseline assessment or monitoring data that may exist from previous or current projects (for subsection 3.2)
- GIS analysis of coastal spatial change from comparison of historical air photography (for subsection 3.3)
- LiDAR surface elevation data either within the mangroves or landward that may be available from a government lands department or private company (for subsection 3.4)
- Tide gauge data that can be analyzed to show relative sea level trends (for subsection 3.5).

Sources of tide gauge data include:

Most global tide gauge records are compiled at the *Permanent Service for Mean Sea Level* (<http://www.psmsl.org/data/obtaining/>)

This country tide gauge list starts at Europe and progresses around the world towards the east. A record of at least 30 years gives a reliable indication of relative sea level trends.

South Pacific Sea Level and Climate Monitoring Project (<http://www.bom.gov.au/oceanography/projects/spslcmp/spslcmp.shtml>)

NOAA Tides and Currents (<http://tidesandcurrents.noaa.gov/sltrends/index.shtml>)

- Data on sedimentation rates under mangroves, although this is rare unless previous scientific research has been conducted at the site. Literature searches can be conducted on databases such as Google Scholar using “sedimentation, mangrove, [the country name]” as search terms (for subsection 3.6)

- Results from adjacent ecosystem monitoring, such as extent and health of sea grass or inshore coral reefs and catchment records on river discharge (for subsection 3.7)
- Downscaled climate models of future climate change scenarios for the area that may be available through other projects or key stakeholders such as government departments of meteorology or climate change and regional climate change research institutions (for subsection 3.8)
- Observed trends in river flow and historic rainfall patterns in catchments of rivers flowing into mangrove areas (for subsection 3.8)
- Local community knowledge compiled in social science publications, or from journalistic sources (for subsection 3.9)
- Reviews of environmental legislation that protects wetlands and mangroves (for subsection 3.9)
- Information compiled on mangrove resource usage, such as government records of fishing licenses, fish catches or forestry (for subsection 3.9)

Initial reviews of existing coastal zone management plans and other types of vulnerability assessments/adaptation plans for the area or region can also help the project. These may contain components from the above list or can be incorporated into the process of prioritizing adaptation actions (Section 5).

The desktop review of existing information acts as a scoping step and is a good way of identifying and involving stakeholders who may have supporting information or expertise. The WWF pilot projects in Cameroon, Tanzania and Fiji held inception workshops to introduce the project while also inviting stakeholders and those involved in other coastal management or climate change projects to give presentations on their work. Through this process, a range of background information and expertise was identified early in the vulnerability assessment.

## 3.2 Forest assessment of mangroves

Approach	Expertise/ Technology needed	Time taken	Cost	Contribution to VA
Rapid	Some	Moderate	Some	Rather high
Plots	Moderate	Rather high	Moderate-Rather high	High
Litter	Moderate	High	Moderate	Some

### What is it?

The mangrove forest assessment survey provides a baseline of current forest condition, which is a sensitivity factor. The survey defines the mangrove area, identifies species zones that make up that area, assesses forest condition and quantifies biomass and productivity.

The mangrove forest assessment survey provides a quantitative baseline from which change over time can be identified in future. This is a measure of adaptive capacity.

### Why do it?

The specific objective of this component is to establish a quantitative baseline of relevant biological parameters for mangrove zones most likely to be affected by climate change, against which to monitor future change.

Results can be used to analyze the causes of any observed change in relation to natural and anthropogenic pressures, particularly identifying or separating those that might be correlated to changes in climate parameters, whether direct or indirect.

### Sample design

The study area should be a landscape/seascape unit, such as a delta, rather than an entire country. The scale should be such that exposure factors are fairly uniform within the study area (subsection 2.4).

The methods described in this subsection – transect line rapid assessment, permanent plots and mangrove litter productivity – are based on internationally recognized standard methods (English et al., 1997; Caribbean Coastal Marine Productivity, 2000; Ellison et al., 2012). Use of accurate and validated methods

for determining ecological integrity is a useful contribution to decision makers (Borja et al., 2008). Use of standard methods allows comparison of results with existing published data sets. These established forest assessment methods are used here to answer questions specific to climate change vulnerability.

Sampling is carried out using a shore-normal transect design along a line across the mangrove area from land to sea. Such a design places one transect passing through the apparent centre of the mangrove area or bay and adds sequentially spaced transects to each side as required to cover the mangrove area, as resources allow.

Within a given transect, the following sites are of most interest:

- lower zones along the seaward edges of river deltas and coastal mangroves, because the lowest elevation zones are most vulnerable to increased inundation stress
- on the boundary areas between two zones within a mangrove forest, where inland migration may be occurring
- upper zones along the periphery of saline flats and the landward edges of mangroves bordering terrestrial grassland or forest, where inland migration may be occurring

Described below are three levels of baseline assessment, which progressively build on one another.

- **Subsection 3.2.1:** A rapid assessment establishes what mangrove forest community structure is present, and what condition the forest is in. It is good for a reconnaissance survey with local community members and can be combined with ground-truthing for GIS analysis (subsection 3.3).
- **Subsection 3.2.2:** Permanent plot measurement gives quantitative forest assessment data that are most useful to the assessment of vulnerability and change.

- **Subsection 3.2.3:** A mangrove litter productivity study gives more detailed information on mangrove health and phenology.

### 3.2.1 Rapid assessment

A rapid assessment establishes what mangrove forest community structure is present, and what condition the forest is in. It is good for a reconnaissance survey with local community members and provides a low-technology baseline against which future change can be identified.

#### How to collect data

- Determine the extent of the mangrove forest using the most recent aerial photographs available (or Google Earth).
- Examine the aerial photographs and identify any species zones in the mangroves as shown by different shading. *Rhizophora* and *Bruguiera* tend to be dark green, while *Avicennia*, *Sonneratia* and *Nypa* all tend to be pale green. Identify and record the coordinates of features such as gaps and paths to help plan the field trip.
- Copy or print the aerial photograph. Mark the vegetation zones on the copy. Include a scale and identify the direction of north. (Take this copy into the field to accurately check the types and positions of the zones, ground-truthing the aerial evidence on the photo.)
- Mark several transects perpendicular to the coastline on the copy. Have one transect passing through the apparent center of the mangrove area or bay, and add sequentially spaced transects to the left and right as resources allow.
- Mark any prominent landmarks or geomorphic features, such as creek channels, on the copy. They will help you to identify the transect lines when in the field.
- Check the tide predictions to choose a good period for fieldwork. It is best to have low tide happening in the middle of the day. Ask local community members whether they are available to help.
- Collect the equipment required.

#### Equipment Required

- Handheld GPS
- Pencils and copies of data sheet (in Appendix)
- Clipboard
- 50 m measuring tape (open reel is best in mangrove mud)
- Magnetic compass
- Copies of aerial photos of the area
- Brightly colored flagging tape
- Copy of Table 6
- Personal safety gear

- Begin fieldwork. Transects can start from the seaward edge or landward margin (depending on tides and access), traversing across the mangrove area to the opposite edge. The landward margin is where just a few mangrove trees are present among freshwater or dryland vegetation. Use major features visible on the aerial photograph to determine the location of this point and the transect line. Identify and record a waypoint for the transect start position using the GPS, and write this position on the data sheet (see Appendix).
- Walk the transect line using a compass or GPS to ensure that the transect remains perpendicular to the shoreline and straight. Along the transect, record the margins of each mangrove zone (e.g., species-dominant section), the width of each zone and the seaward edge. For each zone, select an observation point along the transect on the landward edge, in the center of each mangrove zone, at each zone margin and at the seaward edge. Within a 15 m radius, record information on the data sheet about which species are present and which are abundant or rare. Although mangrove zone changes usually have a mixed transition area, the line between two zones is where one species is more dominant on one side and another species is more dominant on the other side.
- At each observation point, also record the mangrove condition in an area within a 15 m radius. Impact (human or natural) is assessed on a scale from 1 to 5 where 1 is no impact and 5 is severe impact (Table 6).

Code	Condition	% cover canopy	Example
1	No or slight impact	76-100	Fairly continuous canopy of trees but possibly some gaps and regrowth. Isolated damage to trees or saplings.
2	Moderate impact	51-75	Broken canopy of trees with lower regrowth and recruitment areas. Some trees cut and stripped.
3	Rather high impact	31-50	Tree canopy uneven; majority of the area not showing regrowth; bare mud.
4	High impact	11-30	Only a few trees remaining at canopy height. Extensive clearance and some recruitment; large areas of bare mud.
5	Severe impact	0-10	Extensive clearance to bare mud, little recruitment, few trees remain alive.

**Table 6. Codes used to record mangrove ecosystem condition and human or natural impact (adapted from Table 3.5, English et al. 1997).**

- k) Consult with local community members and try to determine why any impact is occurring. In some areas, mangroves are naturally spaced and stunted owing to conditions such as high salinity, so local knowledge of how healthy the mangroves appear to be in different habitats is useful for comparison. Because any impact may be direct, indirect, or both, it is important to record any phenomena such as erosion, tree cutting, storm damage, etc.
- l) At each site, rank the presence of seedlings on an ordinal scale of 1–5 to determine a recruitment score, using the scale below. Record the score in the final column (S = score)

Rank	1	2	3	4	5	S
<b>Sensitivity factors</b>						
Recruitment	All species producing seedlings	Most species producing seedlings	Some species producing seedlings	Just a few seedlings	No seedlings	

**How to analyze results**

Compare impact codes from site to site and at particular sites over time, such as from year to year. Use the impacts identified to consider how to improve resource management and local community knowledge and capacity, which will build adaptive capacity. Measurement of mangrove zone width and identification of species in each zone provides ground verification information for the spatial mapping step in subsection 3.3.

**How to interpret vulnerability**

Mangroves in poor condition, such as those suffering from unsustainable exploitation, will have reduced resilience to climate change-related perturbation. This factor will increase their sensitivity to climate change impacts.

Sea level rise impacts may include consistent mortality of trees at the seaward edge, along with sediment erosion. Storm or large wave impacts can cause tree damage or erosion at the seaward edge, but this tends to be patchy rather than consistent along the shore and later recovers. Sea level rise impacts may also include mortality of species in inner zones, although this may coincide with the ecosystem adapting by the establishment of mangrove seedlings inland from where a particular species previously grew.

Using the scale on the following page, rank the mangrove area’s vulnerability using the scores from Table 6, taking an overall average for the mangrove area. Detailed site-by-site scores can be used to assist in monitoring and management, prioritizing areas that need rehabilitation. Also score the presence of seedlings, because recruitment is an indication of both mangrove health and adaptive capacity. Record each score in the final column (S = score).

Rank	1	2	3	4	5	S
<b>Sensitivity factors</b>						
Mangrove condition	No or slight impact	Moderate impact	Rather high impact	High impact	Severe impact	
Recruitment	All species producing seedlings	Most species producing seedlings	Some species producing seedlings	Just a few seedlings	No seedlings	

**Strengths/weaknesses**

The rapid assessment technique is a good approach to reconnaissance of the area to help in planning more detailed work. Rapid assessment is also a useful exercise in which to involve local community members, in both evaluation and identification of impacts. Linking this with observation of resource decline can encourage local capacity building for better resource management.

Mangrove species zone identification and zone width measurement provide useful ground verification information for GIS analysis of recent changes in

mangrove spatial cover as described in subsection 3.3. It is most efficient if these sections of the fieldwork are carried out at the same time by the same staff, or, if undertaken by different consultants or project staff, that information is shared.

The condition categories are quasi-quantitative and will vary between assessors, particularly in the central categories. Accuracy is improved if the same person revisits the sites or if clear criteria are recorded for deciding on impact codes. However, any statistical analysis of the data should be carried out with caution.



Photo: Joanna Ellison

### Case study: Fiji

The zonation and conditions of the Lomawai mangrove forest in Fiji were assessed across two shore-normal transects, shown in Figure 6, as well as two sample sites further to the north. Transect-based species identifications and zone measurement also allowed for ground-truthing of this mangrove area map, which was developed in combination with analysis of aerial imagery (subsection 3.3).

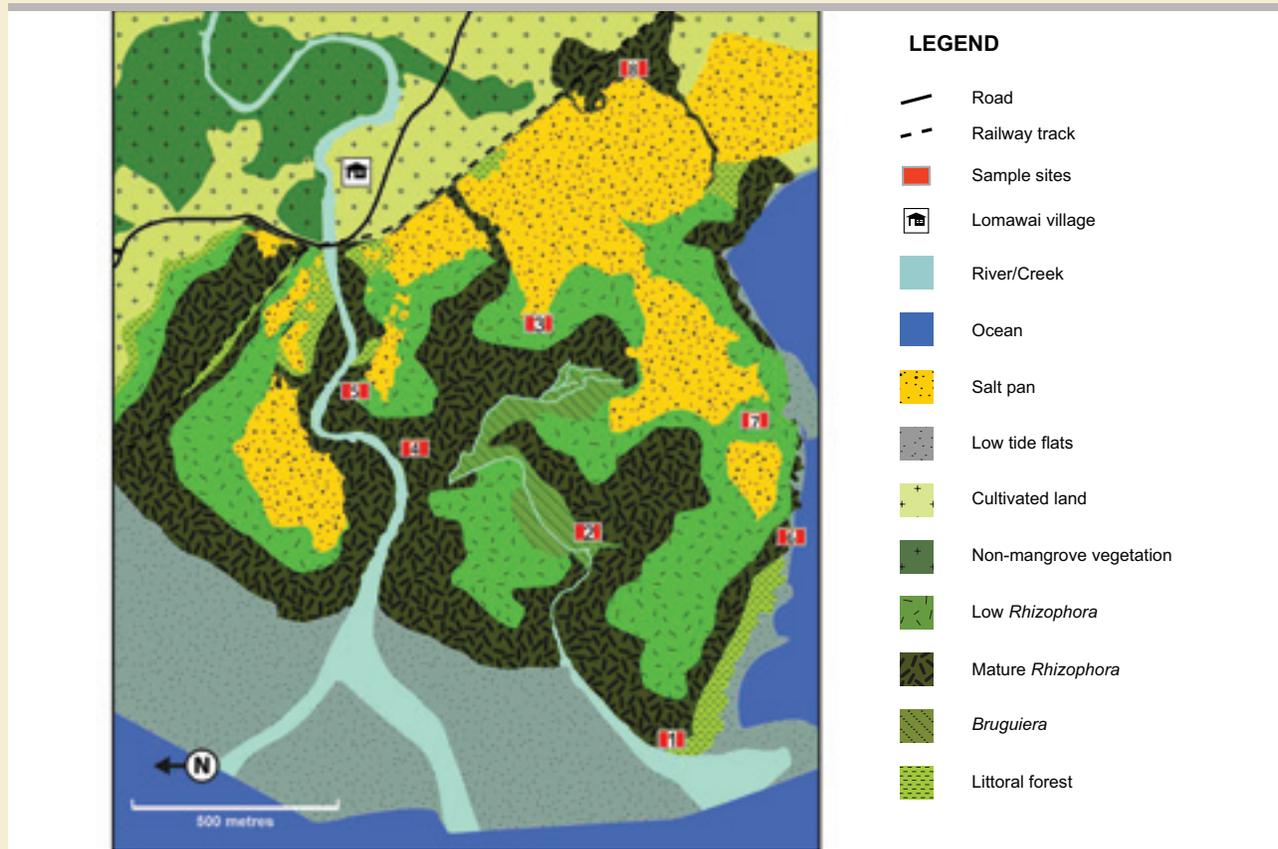
Condition assessment results from the initial survey and subsequent remeasurement are shown in Table 7.

Results show some human disturbance impacts in 2002 caused by cutting trees and stripping the bark from *Bruguiera* trees for use in dyes. Since 2000, WWF has helped the local community develop reserves in the mangrove area, involving community members in mangrove monitoring and management planning. This has resulted in reduced human impact in the

Sample site	October 2002	June 2007	October 2010
1	3	1	1
2	1	1	1
3	–	1	1
4	3	2	1
5	3	2	1
6	1	1	1
7	1	1	1
8	3	2	1

**Table 7. Mangrove condition assessment results from the Lomawai Reserve, Fiji, using condition rankings from Table 6.**

mangrove area as shown by the later results (2007 and 2010) in Table 7. Examples of condition assessment are shown in Figures 7 and 8.



**Figure 6. Mangrove rapid assessment sites at the Lomawai Reserve, western Viti Levu, Fiji.**

By Michael Helman



Photo: Brigid Morrison

**Figure 7. *Bruguiera gymnorhiza* forest, Fiji. This site scores mangrove condition = 1 (no or slight impact) and seedlings = 1 (all species producing seedlings).**



Photo: Joanna Ellison

**Figure 8. *Bruguiera/Rhizophora* forest, Fiji. There are very few seedlings, numerous light gaps and trees stripped of bark. This site scores mangrove condition = 3 (rather high impact) and seedlings = 4 (just a few seedlings).**

Overall, the Lomawai rapid assessment scored:

Rank	1	2	3	4	5	S
<b>Sensitivity factors</b>						
Mangrove condition	No or slight impact	Moderate impact	Rather high impact	High impact	Severe impact	1
Recruitment	All species producing seedlings	Most species producing seedlings	Some species producing seedlings	Just a few seedlings	No seedlings	1

### Case study: Tanzania

A rapid assessment was carried out in 2007 and 2009 in Tanzania’s Rufiji Delta (Wagner & Sallema-Mtui, 2010) to obtain data on mangrove condition, presence of seedlings, as well as the presence of stumps. Figure 9 shows a number of shore-normal transects used for this assessment.

Examples from the rapid assessment are shown in Figures 10 and 11.

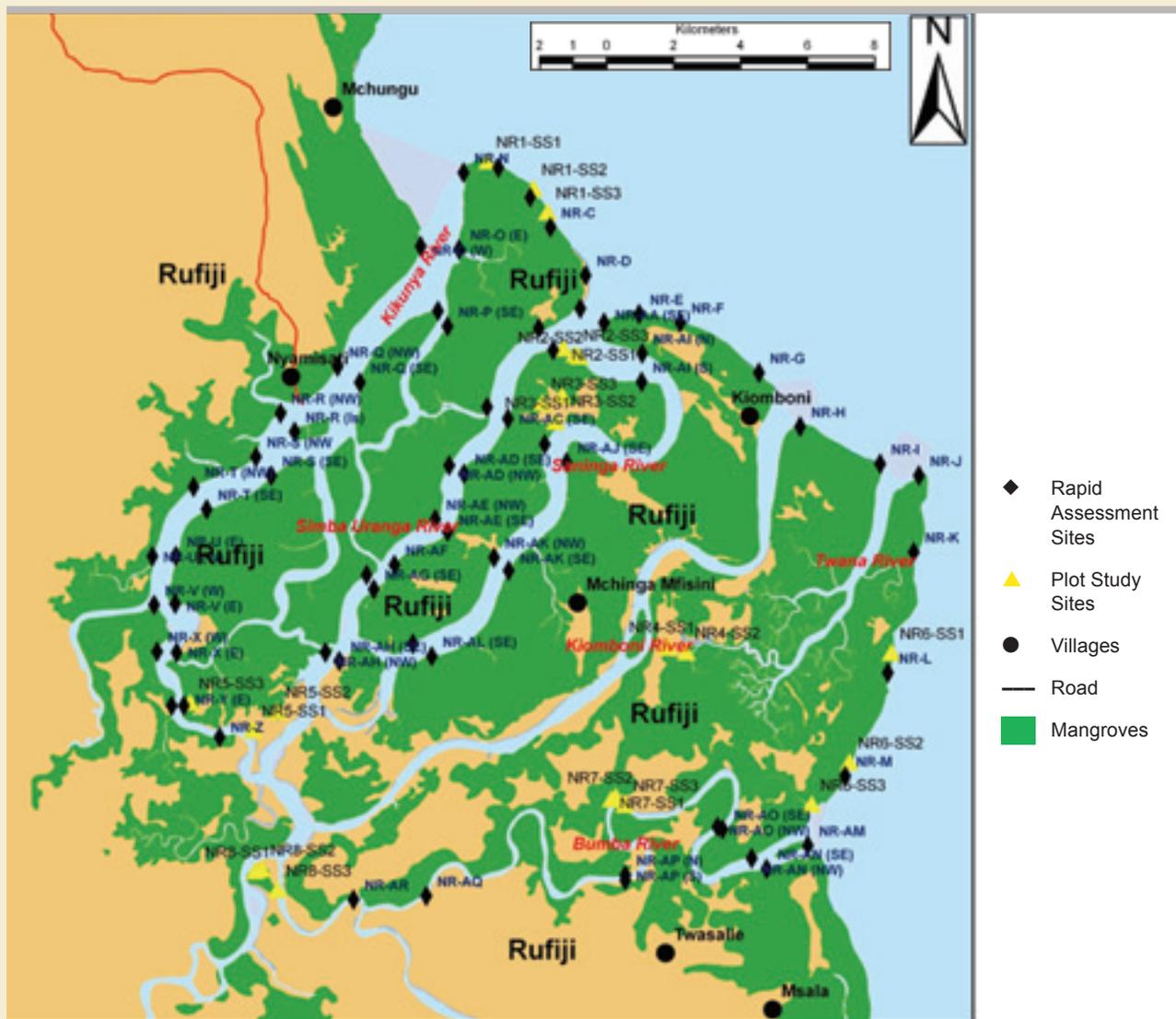


Figure 9. Map of the North Rufiji Delta, Tanzania, showing rapid assessment and permanent plot study sites (from Wagner & Sallema-Mtui, 2010). All these sites have an NR prefix to designate North Rufiji.

By Haji Mwachano



Photo: Greg Wagner

**Figure 10. Accretion and growth of new stands of *Avicennia* occurring at Subsite NR1-SS2 due to input of sediments from a small outflow stream (Wagner & Sallema-Mtui, 2010). This site scores mangrove condition = 1 (no or slight impact) and seedlings = 1 (all species producing seedlings).**



Photo: Greg Wagner

**Figure 11. Subsite NR1-SS3 on the seaward edge of Simba Uranga Island showing erosion as well as fallen *Rhizophora* trees and stumps (Wagner & Sallema-Mtui, 2010). This site scores = 4 (high impact) and = 5 (no seedlings).**

Overall, the Rufiji Delta rapid assessment scored:

Rank	1	2	3	4	5	S
<b>Sensitivity factors</b>						
Mangrove condition	No or slight impact	Moderate impact	Rather high impact	High impact	Severe impact	1
Recruitment	All species producing seedlings	Most species producing seedlings	Some species producing seedlings	Just a few seedlings	No seedlings	1

### 3.2.2 Permanent plots

Permanent plots in each mangrove zone can give a quantitative assessment of mangrove biomass and provide a stronger baseline for assessment of change over time, such as differential growth or mortality of one species. Such permanent plots in each zone record community structure, height and diameter of trees and density of seedlings. These are standard forestry assessment methods (Philip, 1994) that are also used in mangroves (English et al., 1997; CARICOMP, 2000; Ellison et al., 2012).

Permanent plots, as their name suggests, can be revisited in future years to show long-term change. Although this may not be possible within the timeframe of a specific project, permanent plots are an invaluable investment that can be taken advantage of by future projects, allowing longer-term monitoring and evaluation of trends in vulnerability and the effectiveness of adaptation options. Hence, the methods described below include some hints on how to make the plots more versatile for longer-term reuse and remeasurement.

#### How to collect data

- a) Collect all the equipment required.

#### Equipment Required

- PVC or other durable stakes to mark plot corners
- Small metric tape measures (e.g. sewing tape measures) with mm intervals
- Numbered aluminum tree tags (may be available at a forestry department)
- Aluminum, stainless steel or brass nails of 4-5 cm length
- Hammers
- Metal wire or heavy-duty cable ties
- Wire cutters (if metal wire is used)
- Extending surveyor's staff (can be borrowed from a survey department)
- Handheld GPS
- Pencils and copies of data sheets (In Appendix)
- Clipboard
- 50 m measuring tape (open reel is best in mangrove mud)
- Magnetic compass
- Copies of aerial photos of the area
- Brightly colored flagging tape
- Personal safety gear

- b) On the transect established in subsection 3.2.1, choose a sampling location in the center of each mangrove zone, selecting an area for each plot that appears to be characteristic of the zone based on the aerial photo and a reconnaissance of the site. Avoid unique locations, such as next to a tidal creek or a disturbance.
- c) Each plot should be 10 x 10 m in dimensions. If the trees are very dense, this can be reduced to 5 x 5 m; if the trees are very large, it can be increased to 20 x 20 m. Although one plot per zone is the cheapest option, results are far better with replicates (other adjacent plots). This improves the rigor of monitoring, as greater sample size gives more robust statistical analysis.
- d) Mark the corners of each plot with a stake or other durable mark and use the GPS to identify the location of each corner. For each tree in the plot, hammer in a tag at around 1.3 m above the mud level (a convenient height for most adults) using a rust-resistant nail and a rust-resistant numbered tag. Choose a section of the trunk that is blemish-free and below any major branches. If all tags in the plot face one direction, such as landward, this will make them easier to find years later when remeasuring, as they get covered with barnacles, moss and silt. On *Rhizophora* trees, measure the tree circumference above where the roots converge and below where the branches spread. Where trees branch low, tag and measure all limbs at 1.3 m and circle them together as one tree on the data sheet.
- e) Measure the circumference of the tree at 2 cm above the height where the tag was installed, as this avoids any scar bumps that may develop and makes any future remeasurement simpler. This is the GBH (girth at breast height) measurement – a standard technique in forest assessment from which DBH (diameter at breast height) can be calculated. Record the tree tag numbers and measurements on the data sheet.
- f) If the tree is too small to hold a nail, then put the tag on a loop of stainless steel wire or a heavy-duty cable tie and clasp this onto a suitable low branch to stop it from slipping down. Measure the circumference 2 cm below the nail and below the branch. The diameter can be calculated later from the circumference. Forestry departments may have specialized diameter measurement tapes, but they

are not necessary. Measuring can be accomplished with a sewing tape and a geometry calculation.

- g) Sketch a map of where each of the numbered trees is located in the permanent plot, also marking the direction of north (see Appendix). This makes it possible to find trees that may have lost their tags when the plot is remeasured.

### How to analyze results

Survey plot results are analyzed using the following calculations. It is best to do this using software such as Excel, and its formula functions.

$$\text{Tree density} = \frac{\text{Number of trees}}{\text{Plot area}}$$

This can be broken into trees of different species if plots are of mixed species, such as *Rhizophora* or *Avicennia*.

If the plot was 5 x 5 m then the plot area is 25 m<sup>2</sup>. WWF pilots found that it was best to report results per plot size rather than convert to per hectare, as readers find it easier to visualize a smaller area while per hectare calculations give huge numbers that can be difficult to understand.

Relative frequency shows the relative dominance of different species if more than one are present.

$$\text{Relative frequency \%} = \frac{[\text{Frequency of species A}]}{\text{Total tree count}} \times 100$$

Convert the tree circumference measurement into diameter using the formula below. If a diameter measurement tape was used, this step is not necessary. If a linear (cm) tape, such as a sewing tape, was used, then use this conversion:

$$\text{Tree diameter (DBH)} = \frac{\text{Measured circumference (in cm)}}{3.142}$$

Keep this measurement in centimeters rather than convert to meters, as it keeps the calculations easier.

3.142 is the constant  $\pi$  (called pi, sometimes spelled phi) used in standard circle geometry calculations.

Some simple plot comparison statistics can then be calculated:

$$\text{Mean DBH} = \frac{\text{Total of DBH}}{\text{Total trees in plot}}$$

$$\text{Mean height} = \frac{\text{Total of tree height}}{\text{Total trees in plot}}$$

The DBH measurements can also be used to calculate the basal area (BA) of mangroves, which is one of the best measures of mangrove abundance and is generally proportional to canopy cover. It is also one of the best indicators of ecosystem health and maturity (greater DBH indicates greater health). Also, when calculated by species, the basal area indicates the relative importance or dominance of each species in a given site.

The basal area is the cross-sectional area of the tree stem at 1.3 m above the ground where it was measured.

$$\text{The basal area of a tree uses circle geometry (cm}^2\text{)} = \pi \cdot r^2$$

Where r = radius, which is half the diameter (DBH).

So using the DBH measurement,

$$\text{the basal area of a tree (cm}^2\text{)} = \frac{\pi \cdot (\text{DBH})^2}{4}$$

The basal area of the permanent plot is the total of all the tree basal areas in the plot. One must add up the individual basal areas for every tree. It is not possible to use the total plot DBH to calculate the total basal area, as the geometry does not work.

The basal area of the plot = total of tree basal areas (cm<sup>2</sup>) per plot size (such as 25 m<sup>2</sup> in the case of a 5 x 5 m plot).

In the case study below, the units are cm<sup>2</sup> per 25 m<sup>2</sup>. The basal area is commonly reported in forest assessment literature in m<sup>2</sup> per hectare, so convert the plot result data as below depending on the plot size:

5 x 5 m plots:

$$\text{Basal area (m}^2\text{ per ha)} = \frac{0.0001 \times \text{Basal area (in cm}^2\text{ per 25 m}^2\text{)}}{0.0025}$$

10 x 10 m plots:

$$\text{Basal area (m}^2\text{ per ha)} = \frac{0.0001 \times \text{Basal area (in cm}^2\text{ per 100 m}^2\text{)}}{0.01}$$

20 x 20 m plots:

$$\text{Basal area (m}^2\text{ per ha)} = \frac{0.0001 \times \text{Basal area (in cm}^2\text{ per 400 m}^2\text{)}}{0.04}$$

An indicator of community structure is the relative dominance of species, which can be calculated as:

$$\text{Relative dominance \%} = \frac{[\text{Total basal area of species A}]}{\text{Total basal area of plot}} \times 100$$

Biomass of the tree, plot and per hectare, can be determined by the use of allometric equations which have been derived experimentally from harvesting an area and by determining dry weight. There are equations available in the literature for mangrove trees of different statures (Putz & Chan, 1986; Clough & Scott, 1989; Clough, 1992; Clough et al., 1997; Komiyama et al., 2008). This biomass conversion is not required for a mangrove vulnerability assessment, but it demonstrates that these field data can be used to assist with carbon sink calculations that may be useful for mangrove REDD (Reducing Emissions from Deforestation and Forest Degradation) or “wet carbon” projects.

**How to interpret vulnerability**

The results of tree density, relative frequency, mean DBH, mean height, basal area and relative dominance calculations can be interpreted by

- comparison between plots across a transect
- comparison from a transect at one site to a transect at another site
- comparison over time, as shown in the case study below

- comparison of results with published data from mangrove plot measurement that also uses these standard methods (Saenger & Snedaker, 1993; Devoe & Cole, 1998; Soares & Schaeffer-Novelli, 2005; Krauss et al., 2006; Bouillon et al., 2008; Komiyama et al., 2008; Cavalcanti et al., 2009; Kauffman et al., 2011).

Some mangrove forest structure data (Komiyama et al., 2008; Cavalcanti et al., 2009; Kauffman et al. 2011) reveal considerable differences in basal area per hectare across mangrove forests that reflect varying levels of human or natural disturbance impact. Although these studies were not designed to assess vulnerability as shown by basal area, they do include useful basal area data that are indicative of forest conditions. These have been compiled to produce a general indicator scale of forest condition (Table 8). From these studies, three levels of impact could be discerned without over-extrapolating the data, and the basal area for each show considerable differences, although statistical analysis was impeded by lack of primary data. The WWF pilot in the Douala Estuary, Cameroon, that focused on different scales of exploited forest showed that this comparison is a useful way of interpreting forest condition. However, there will be

Source	Location	What was measured	Forest condition			Comments
			1	2	3	
Komiyama et al., 2008	Global, 54 locations	BA m <sup>2</sup> per ha	25.3 n=15	15.2 n= 6	9.8 n=4	Review of other studies
Cavalcanti et al., 2009	Guanabara Bay, Brazil	BA m <sup>2</sup> per ha mean		16.0 ±3.9	13.2 ±4.9	
Pellegrini 2000 & Chaves 2001 in Cavalcanti et al., 2009	Sepetiba Bay, Brazil	BA m <sup>2</sup> per ha range		11.6-61.7		Broad BA range attributed to good state of conservation but strong human influence persisting
Soares 1999 in Cavalcanti et al., 2009	Tijuca Lagoon, Brazil	BA m <sup>2</sup> per ha range		13.3–41.4		
Kauffman et al., 2011	Palau	Mean BA m <sup>2</sup> per ha across zones	34–43			Forest condition understood to be near-pristine
	Yap		41–78			
Ajonina et al., 2011	Douala, Cameroon	BA m <sup>2</sup> per ha mean	31.1	10.3	3.9	WWF pilot site, Cameroon

**Table 8. Compilation of basal area data relative to reported forest condition. Forest condition categories are: 1: minimal impact with traditional use, good conservation, pristine or primary forest; 2: managed or having some conservation status, or secondary forest; 3: affected by natural or anthropogenic disturbance, or concession forest.**

Rank	1	2	3	4	5	S
<b>Sensitivity factors</b>						
Mangrove basal area (m <sup>2</sup> per hectare)	>25	15–25	10–15	5–10	<5	

variations, including the effect of latitude and species type on growth rates.

Basal area change is calculated by comparing basal area from the baseline survey of a plot with the basal area as later remeasured. Mortality is the percentage of trees alive during the baseline survey that are dead or missing when the plot is later remeasured.

If a repeat measurement will not be possible, then basal area results can be compared with those expected for healthy forests (excluding high-latitude or arid sites) by ranking vulnerability on the scale at the top of this page.

The best results for assessment of forest condition as part of the vulnerability assessment would be from a resurvey of the mangrove area at least two years after the initial baseline measurement. This is because basal area results (Table 8) can vary among sites owing to tree density and height, which may be influenced by latitude or salinity. Over time, reduced mangrove health, reduced growth or mortality of mangrove trees are all sensitivity factors; and all indicate increased vulnerability and lower adaptive capacity. It is best to have a project timeframe of at least three years, and to perform the initial and repeat mangrove plot measurements as early and as late as possible in the project.

Recruitment (seedling growth) under mangroves of the same species is normal especially where there are light gaps. Dense seedlings under healthy forest usually suffer from competition unless there is a light gap. However, if there is no seedling recruitment, then this indicates vulnerability.

Vulnerability can be ranked on the scale at the bottom of this page, which can be reported site by site or calculated as an average for the entire mangrove area. Record each score in the final column (S = score).

### Strengths/weaknesses

Permanent plots can show evidence of detailed change related to climate change impacts, such as preferential decline and mortality of one species and succession by another. Permanent plots are a well-described standard technique, so results can be compared with other sites and published results. Results can be used for carbon sink calculations in REDD or “wet carbon” projects.

The biggest problem that the WWF pilots encountered with the remeasurement of plots was tags missing from trees. These pilots found that plastic tags and cable ties do not last. This can be addressed by hammering a secure nail nearly all the way into the tree to affix the tag. If all trees in the plot are tagged on the same side and at the same height, the nail can be found even if the tag has gone. Putting red paint on the tree at the GBH point would also help. If there is a plot map of the relative locations of trees, the trees with missing tags can still be located relative to tags that still exist, and the tags can be replaced.

### Logistical note

The permanent plot fieldwork can be easily combined into the same field trip as the deployment and later remeasurement of low-technology sedimentation stakes (see subsection 3.6.3).

Rank	1	2	3	4	5	S
<b>Sensitivity factors</b>						
Basal area change	Positive	No change	Slightly negative	Moderately negative	Highly negative	
Recruitment	All species producing seedlings	Most species producing seedlings	Some species producing seedlings	Just a few seedlings	No seedlings	
Mortality	<4%	4–10%	10–20%	20–30%	>30%	

### Case study

A forest assessment in Tanzania’s Rufiji Delta was carried out in 2007, with repeat surveys in 2009. Shore-normal transects used delta distributaries for access by boat, and assessments were carried out in the mangroves from these landing points (Figure 9).

Site NR6, Twana Island, is shown in Figure 9 as a seaward edge site on the main section of the Rufiji delta. Plot data showed it to have a fairly high mangrove basal area (over 400 cm<sup>2</sup>/25 m<sup>2</sup> plot = 16 m<sup>2</sup> per hectare) during both 2007 and 2009 (Figure 12) (Wagner & Sallema-Mtui, 2010).

Mangrove species richness remained at two species over the two-year period. *Avicennia* dominated and was the only species found in Subsites NR6-SS2 and NR6-SS3, while *Sonneratia* dominated in Subsite NR-SS1, with some *Avicennia* also present.

Between 2007 and 2009, both *Avicennia* and *Sonneratia* tree density dropped very slightly (Figure 13). Very few saplings were observed in the plots in 2007, and none were observed in 2009, although many saplings were seen just on the seaward side of where the plots were located, indicating that new stands were growing up. *Avicennia* seedling density was very high during both years and showed an increase over the two-year period (Figure 14); however, *Sonneratia* showed very poor recruitment.

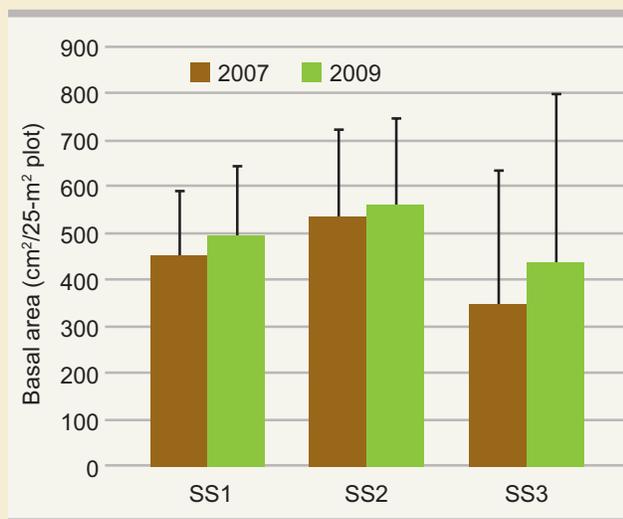


Figure 12. Comparison of mangrove stand basal area (mean and standard error), 2007 and 2009, at site NR6, Rufiji Delta (Wagner & Sallema-Mtui, 2010).

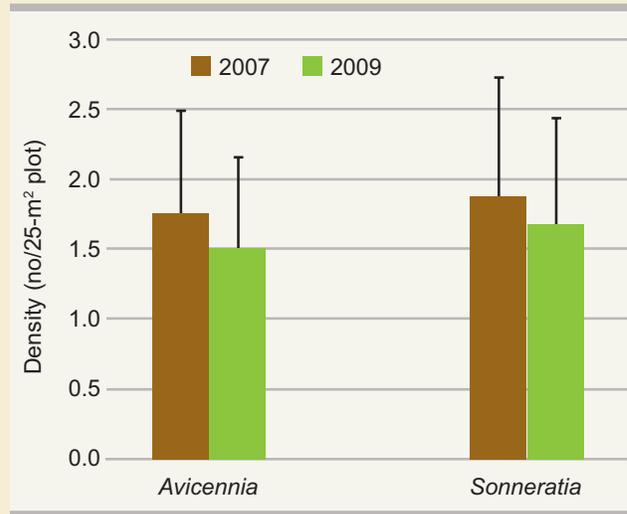


Figure 13. Comparison of tree density (mean and standard error) by species, 2007 and 2009, at site NR6, Rufiji Delta (Wagner & Sallema-Mtui, 2010).

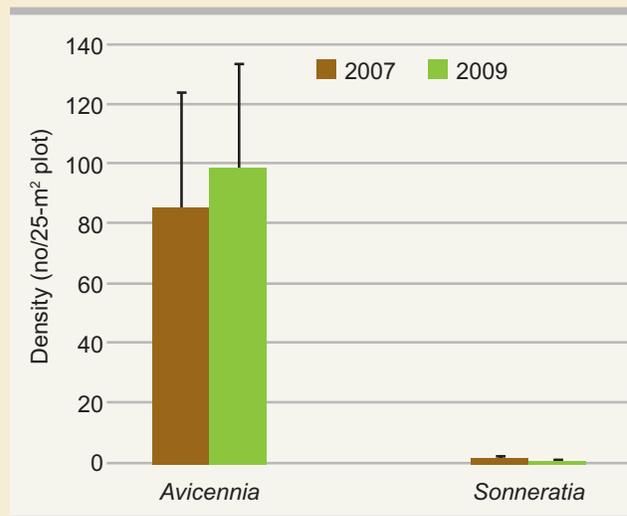


Figure 14. Comparison of seedling density (mean and standard error) by species, 2007 and 2009, at site NR6, Rufiji Delta (Wagner & Sallema-Mtui, 2010).

Therefore, in terms of vulnerability assessment, this coastal section is showing resilience, since trees show growth and seedlings are present. Signs of reduced resilience would be lack of growth of trees, failure of seedlings to grow into saplings and poor seedling presence. At this site, *Avicennia* seedlings were

present, but *Sonneratia* was not present, which may indicate loss of resilience and should be monitored in the future.

Overall, the Rufiji Delta mangrove forest assessment scored as follows:

Rank	1	2	3	4	5	S
<b>Sensitivity factors</b>						
Mangrove basal area (m <sup>2</sup> per hectare )	>25	15–25	10–15	5–10	<5	2
Basal area change	Positive	No change	Slightly negative	Moderately negative	Highly negative	1
Recruitment	All species producing seedlings	Most species producing seedlings	Some species producing seedlings	Just a few seedlings	No seedlings	1
Mortality	<4%	4–10%	10–20%	20–30%	>30%	1

### 3.2.3 Litter productivity analysis

Reduced mangrove productivity indicates increased vulnerability and lower adaptive capacity. Mangroves in poor condition, such as those suffering from unsustainable exploitation or inundation stress, are more sensitive to climate change perturbation.

Phenology is the timing of fruiting and flowering, which is influenced by climate, particularly rainfall patterns and of significance for pollination. Significant change in phenology indicates sensitivity and increased vulnerability.

Such impacts can be identified from mangrove litter surveys. Litter in this context means the productive fall from a forest. Data on litter fall collected for a minimum of one year can show vegetative production (grams of production per m<sup>2</sup> of mangrove forest) and phenology. These data are useful for climate change identification and productivity calculations, as well as for broader monitoring of forest health. It is a sign of stress when trees fail to produce fruits.

#### How to collect data

- a) Make litter catchers (Figure 15) using the following equipment.

#### Equipment Required

- 4 m of 4 cm diameter PVC pipe
- 4 PVC corners to fit
- Glue to stick these together into a square
- About 2 m<sup>2</sup> of shade cloth or fine netting
- Small plastic cable ties to attach net to the pipe
- Rope to hang catcher in trees

#### Also:

- Plastic bags and marker pen for the samples
- 60°C drying oven
- 2 decimal place balance
- Large drying trays
- Personal safety gear

- b) In each permanent plot, hang litter catchers in the trees above the reach of tides at a minimum of three per plot. Empty each catcher monthly into a labeled plastic bag.
- c) Place each sample in a large drying tray at a laboratory. Dry the catch of each sample in the oven at 60°C for two days. Then sort into leaves, fruit, flowers and wood and weigh each component (see data sheet in Appendix). Frass, mainly insect remains, is the black powder left behind when all the other parts have been sorted from the collection.



Photo: Joanna Ellison

**Figure 15.** Litter catcher hung in a *Rhizophora* forest, Fiji.

**How to analyze results**

Mean litter production can be calculated from the total of all of the litter traps in each plot, and averaged for the whole study site and reported in dry weight per square meter per day by dividing the mean by the number of days between collections. These results can be compared with other studies using this standard technique (Saenger & Snedaker, 1993; Bouillon et al., 2008; Komiyama et al., 2008) to show relative productivity trends.

Overall, results can be interpreted by

- comparison between plots across a transect
- comparison from a transect at one site to a transect at another site
- comparison over time
- comparison of results with mangrove productivity results from similar sites elsewhere

The best results are obtained from repeat measurements over time, as mangrove productivity

results vary between sites owing to tree density and height, which may be influenced by latitude or salinity.

**How to interpret vulnerability**

Declines in mangrove condition can be inferred from litter productivity results that show little or no flowering or reproductive parts or less than expected productivity compared with sources such as Duke et al. (1981), Saenger & Snedaker (1993) and Bouillon et al. (2008).

Compare site productivity results with those to be expected for healthy mangrove forests in the relevant latitude and climate (Bouillon et al., 2008; Komiyama et al., 2008). When trees are stressed, they reduce flowering and fruiting, which is commonly 20 to 30 percent of productivity, and also reduce leaf productivity. Hence the presence of flowers or fruits during their normal season is one simple way of determining mangrove health.

Vulnerability can be ranked on the scale below, which can be reported site by site or calculated as an average for the entire mangrove area. Record each score in the final column (S = score).

**Strengths/weaknesses**

Our pilots found litter productivity analysis to be a labor-intensive technique, requiring scientific equipment and a great deal of time. Most sites did not use the approach for this reason.

If undertaken, litter productivity analysis would be a good subproject in which to involve a high school or college science class, and which would be undertaken for just one year to get a baseline and then repeated every five years to show any changes.

Rank	1	2	3	4	5	S
<b>Sensitivity factors</b>						
Litter productivity	High, including >20% fruits and flowers	Medium, including 5–20% fruits or flowers	Medium, with few fruits or flowers	Low (excluding wood)	Mainly wood	

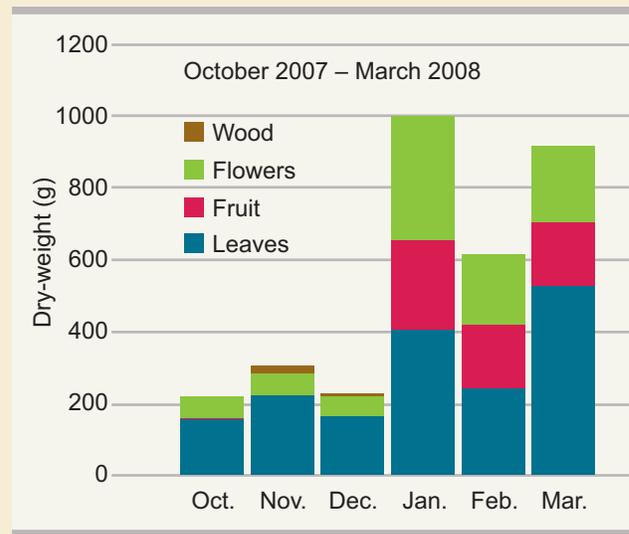
### Case study

Mangrove leaf litter catchers were deployed in Tikina Wai, Fiji, by a local community working with project consultants from the University of the South Pacific who were carrying out the mangrove vegetation fieldwork. Because leaf litter catchers appear similar to fishing devices (Figure 15), there were some initial isolated cases of equipment loss, but as understanding of the project increased in the community, this ceased.

The mangrove monitors (ladies from each village who had been nominated by the community to support assessment efforts in the mangrove area) collected the leaf litter monthly and sent samples to the university in the capital city. Figure 16 shows some of the results: little wood production overall, indicative of a lack of storms and domination by leaf production, which rises with the onset of summer in late December. The maximum times for flowering and fruiting occur from January to March. (Note that a litter study is best carried out for 12 months duration so that annual productivity can be calculated from the totals for each month.)

Such data can be compared with other studies to show relative sensitivity to climate change impacts. In Fiji, Tyagi and Pillai (1996) demonstrated significant differences in flowering and fruiting between mangrove communities in the wet and dry zones of Fiji. The mangrove species of *R. stylosa*, *R. samoensis* and *B. gymnorhiza* all showed more flowering in the wet zone relative to the dry. However, differences

in propagule setting between the zones were less significant. Further analysis by Tyagi (2001) found that, during a drought year, the number of flowers and propagules produced per plant was significantly lower than during a non-drought year. In the case of dry weather conditions, stress causes mangroves to reduce reproduction.



**Figure 16. Six months of litter analysis results from Bole, Tikina Wai, showing the onset of summer fruiting in January (Tuiwawa & Rounds, 2010). Flowering and fruiting exceeds 20 percent of productivity, indicating a healthy forest.**

Hence, this site scores as follows:

Rank	1	2	3	4	5	S
<b>Sensitivity factors</b>						
Litter productivity	High, including >20% fruits and flowers	Medium, including 5–20% fruits or flowers	Medium, with few fruits or flowers	Low (excluding wood)	Mainly wood	1

### 3.3 Recent spatial changes of mangroves

Approach	Expertise/ Technology needed	Time taken	Cost	Contribution to VA
GIS analysis	High	Moderate	Moderate	High

#### What is it?

Identification of spatial changes in mangrove vegetation cover is carried out through comparison over time of a series of aerial photographs and/or satellite images. This is frequently referred to as a GIS (Geographic Information Systems) study because of the software, such as ArcView, used to analyze the data.

Retreat of the seaward edge of mangroves and reduction in overall mangrove area over time are sensitivity factors.

#### Why do it?

Vulnerability is shown by change in mangrove area over time. Sea level rise impacts are shown by consistent mortality and retreat at the seaward edge and inland recruitment at the landward edge.

Lack of spatial change shows resilience of the mangrove system over time, which maintains older-growth trees and better reproductive success. Expansion of the seaward edge over time suggests either a strong sediment supply or sea level fall and is a sign of good mangrove resilience. Retreat of the seaward edge over time, if consistent along the coast, very likely shows vulnerability to sea level rise. However, spatial change, such as retreat of the seaward edge, does not necessarily indicate erosion as mangroves could have died back owing to excess sediment deposition. Field surveys of areas that show change through GIS analysis will assist identification of causes. These surveys are best combined with the rapid forest assessment (subsection 3.2.1).

GIS analysis can identify and quantify mangrove retreat at the seaward edge, recruitment inland (Lucas et al., 2002; Gilman et al., 2007b) or stability of mangrove distributions to demonstrate long-term resilience. This analysis provides context to the forest assessment results from subsection 3.2, and

can identify causes of any decline in mangroves by assessment of their spatial occurrence.

In addition to climate change impacts, the results of spatial analysis can help show areas of human impact that could be targeted for rehabilitation.

#### How to collect data

Compile information on existing aerial photographs and satellite imagery of the mangrove area. Tabulate an inventory of its date, scale, type, whether color or black and white, availability, cost, tidal state at time of image and cloud cover or other issues affecting quality.

The earliest aerial photographs are usually from the 1940s and will be held by archival libraries or government departments. Government lands, survey and environment departments usually hold imagery in GIS departments or units. Satellite imagery is available since the 1970s (Green et al., 1996; Heumann 2011), from sources listed in Table 9.

- (a) Select the best imagery (preferably including the oldest and most recent), using as criteria the image's clarity, date and coverage. Imagery taken at low tide is preferable to that taken at high tide, as more detail of the mangroves is visible particularly if the site has turbid water.
- (b) Atmospherically correct and geo-rectify images, using commonly applied remote sensing techniques (Green et al., 2000), such as control points of features that are visible on different images.
- (c) Identify mangrove areas from the image, using methods listed in Table 10 for mapping mangrove extent and mapping mangrove change over time. Fieldwork results from subsection 3.2.1 can be used to ground-truth aerial imagery.
- (d) Ground-truth species zones to verify the spectral signatures for different species composition zones. (This can be combined with rapid assessment procedures in subsection 3.2.1.)

Data	Resolution and dates	Coverage	Cost	Source	Notes
Landsat	~30 m 1973–present	Global; 170 x 180 km scenes	Free; some data from SE Asia still sold commercially (US\$425/scene)	Searchable image archive: <a href="http://glovis.usgs.gov">http://glovis.usgs.gov</a>	Consistent sensor useful for long time series, change detection
ASTER	~15 m 2000–present	Global; 120 x 150 km scenes	Georeferenced Jpgs are free (no analysis); raw imagery sold for US\$80/scene	Searchable image archive: <a href="http://glovis.usgs.gov">http://glovis.usgs.gov</a>  Free georeferenced jpgs are downloaded from the Terralook collection	Visible and infrared bands useful for vegetation mapping; long time series valuable for change detection
SPOT	2.5–20 m 1986–present	Global; 60 x 60 km scenes	2500–4500€/scene; limited data for climate change projects free through Planet Action	<a href="http://www.spotimage.com/">http://www.spotimage.com/</a>  Searchable image archive: <a href="http://catalog.spotimage.com/PageSearch.aspx">http://catalog.spotimage.com/PageSearch.aspx</a>  Planet Action Foundation <a href="http://www.planet-action.org/">http://www.planet-action.org/</a>	Long time series, good spectral resolution for mangrove mapping
IKONOS and GeoEye 1	<1–4 m 2001–present	Limited coverage (on demand); swath width 11 km	US\$7-30/km <sup>2</sup> ; limited data available through GeoEye Foundation	<a href="http://www.geoeye.com">http://www.geoeye.com</a>  Searchable image archive: <a href="http://geofuse.geoeye.com/landing/Default.aspx">http://geofuse.geoeye.com/landing/Default.aspx</a>  GeoEye Foundation <a href="http://www.geoeyefoundation.org/">http://www.geoeyefoundation.org/</a>	Highest resolution available for mapping species, zonation; can be tasked to collect images on demand
QuickBird and WorldView-2	<1–2.6 m 2001–present	Limited coverage (on demand), swath width 14 km	US\$4–30/km <sup>2</sup>	<a href="http://www.digitalglobe.com">http://www.digitalglobe.com</a>  Searchable image archive: <a href="http://browse.digitalglobe.com/imagefinder/main.jsp">http://browse.digitalglobe.com/imagefinder/main.jsp</a>	Highest resolution available for mapping species, zonation; can be tasked to collect images on demand

**Table 9. Most commonly available optical satellite data sources (compiled by Aurélie C. Shapiro, WWF).**

- (e) Identify species zonation and vegetation gaps, seaward edge, landward edge and other significant features and summarize on maps. This will require specialized GIS and satellite remote-sensing skills.
- (f) Compare spatial boundary results from different years of imagery available to analyze spatial trends over time in the mangrove area, showing any movement of mangrove zone boundaries and the seaward/landward mangrove margin over the period covered.
- (g) Use GIS analysis to quantify change over time, identifying areas of loss and gain in each category.
- (h) Ground-truth to validate areas where the GIS analysis shows that there has been change. Check with local communities to verify the change at each site and get some insight as to the reasons for this change (this can be combined with subsection 3.9, Compilation of local community knowledge).

Goal	Methods	Data	References
<b>Mapping mangrove extent</b>	Visual interpretation — with 30 m resolution or less can detect 1–7 classes of mangrove types. Requires longer processing and image specialist skills	Aerial photos, SPOT, Landsat	Gang & Agatsiva, 1992; Roy, 1989; Patterson & Rehder, 1985; Untawale et al., 1982; Manson et al., 2003
	Vegetation index — uses vegetation index algorithms to produce maps of greenness or vegetation health	Multispectral sensors such as SPOT, Landsat	Blasco et al., 1986; Jensen et al., 1991; Chaudhury, 1990
	Classification — the most common method, using unsupervised or supervised techniques, 1–4 classes	Landsat, SPOT, Radar, IKONOS, CASI hyperspectral, aerial photos, ERS, JERS-1	Vits & Tack, 1995; Loo et al., 1992; Woodfine, 1991; Dutrieux et al., 1990; Aschbacher et al., 1995; Mohamed et al., 1992; Eong et al., 1992; Palaganas, 1992; Wang et al., 2004; Vibulsresth et al., 1990; Biña et al., 1980; Green et al., 1998; Woodfine, 1993; Lorenzo et al., 1979; Aschbacher et al., 1995; Alatorre et al., 2011
	Band ratios — dividing pixels in one band or image by corresponding pixels in another band or image	SPOT, Landsat	Gray et al., 1990; Kay et al., 1991; Long & Skewes, 1994; Populus & Lantieri, 1990; Ranganath et al., 1989
<b>Mapping mangrove change over time</b>	Comparing several images from consistent sensors provides information on spatial change	Multiple images from consistent satellite or aerial sensor: Landsat, SPOT, ASTER	Biña et al., 1980; Loubersac et al., 1990; Ibrahim & Yosuh, 1992; Green et al., 2000; Lucas et al., 2002; Held et al., 2003; Manson et al., 2003; Gilman et al., 2007b
<b>Leaf area index</b>	Semi-empirical models using a function of canopy transmittance, solar radiation fraction to determine leaf area index and canopy closure, productivity	Landsat, CASI, IKONOS, SPOT	Green et al., 1998; Kovacs et al., 2005; Kovacs et al., 2009
<b>Mapping mangrove species and zones</b>	Visual interpretation and automated methods — high spatial and spectral resolution to better support mapping of species composition; radar data combined with hyperspectral data visualizes different stands	CASI, IKONOS, aerial photos	Gao, 1999; Green et al., 2000; Vaiphasa, 2006; Verheyden et al., 2002

**Table 10. Mangrove mapping methods (adapted by Aurélie C. Shapiro, WWF from Green et al., 2000; McLeod & Salm, 2006; and Heumann, 2011).**

Leaf area index is a remote-sensing method to determine mangrove productivity. If used, it can add more spatial detail to forest assessment (subsection 3.2). The WWF pilots did not test this method because the technology was found to be unavailable and/or too expensive.

#### How to analyze results

Results are best displayed as maps showing any spatial change of the seaward edge or landward edge of the mangrove area, combined with reporting of mangrove area change, as shown in the Cameroon case study

below. For other examples, see the sources in Table 10 on mapping mangrove change over time.

#### How to interpret vulnerability

Human impacts will show as conversion from mangroves to alternative land uses such as agriculture or coastal development. Mangroves near human settlements may show reduction in tree density due to overexploitation, which can be confirmed on the ground through rapid forest assessment (subsection 3.2.1) and reversed through rehabilitation (subsection 5.1.4).

Rank	1	2	3	4	5	S
<b>Sensitivity factors</b>						
Seaward edge retreat	None	Some	Moderate	Significant	Very significant	
Reduction in mangrove area	None or little	Some	Moderate	Significant	Very significant	

Rank vulnerability on the scale above. Record each score in the final column (S = score).

### Strengths/weaknesses

Many countries have GIS capability in government environment, forestry or lands departments and a range of historical aerial imagery should be archived at these places. Hence, it may not be necessary to purchase all aerial and satellite images available for an area; it may be possible to obtain these through project stakeholders or partners. If the necessary imagery is not available through stakeholders or low-cost sources (Table 9), it may be expensive to obtain, in which case this should be factored into the project budget. Some sites, particularly in equatorial latitudes, have compromised quality of imagery because of cloud cover.

GIS analysis requires specialized skills and software. If these skills are not present in the team or institution, this component may require a consultant. It is, however, a desktop computer-based study that can be carried out remotely from the study area and does not require the passage of time for a comparative result.

Image rectification can be difficult in mangrove areas without permanent features. One further aspect that may be problematic is the uncertainty that may arise due to inaccuracy of the data and processing, which may show change that is not really there. This may be resolved by verifying that any change is outside the error margins of the GIS analysis and by verifying change through interviews with the older members of local communities (see subsection 3.9).

### Case study

Our pilot site in Cameroon proved initially to be the most challenging for this VA component, owing to difficulty in finding imagery as well as the common occurrence of cloud cover. The Douala Estuary on the central Cameroon coast shown in Figure 17 has extensive microtidal mangrove areas dominated by *Rhizophora racemosa*, which accounts for over 90% of mangrove forest including seaward zones. Other species present are *R. mangle*, *R. harrisonii*, *Avicennia germinans* and towards land *Laguncularia racemosa* and *Conocarpus erectus* (Ajonina et al., 2011).

Zouh (2010) acquired satellite images for the Douala Estuary mangrove area through the USGS Landsat image archives referenced in Table 9. These were

provided free of charge but did require a long time to download due to the size of the images as well as the slow Internet connections in Cameroon. The images were downloaded as separate bands and later pre-processed by stacking the separate layers together, re-sampling the images to the same spatial resolution and finally sub-setting the images. Landsat imagery was used for this study because Landsat has the longest image archive, dating back to 1973. However, due to heavy cloud cover, which is common in the tropics, the oldest cloud-free image of this area was from 1975. Table 11 provides basic information about the images used for analysis, complimented by ground-truth data (Zouh, 2010).

An example of results from a landward site 1 and a seaward site 2 (shown in Figure 17) are given in Figures 18 and 19. The landward edge at Yoyo is shown to be stable over the time period, indicating resilience to any human or natural disturbance (Figure 18). By contrast, the seaward mangrove island, Kwelekwele Island, has been losing area over the time period, indicating strong vulnerability to rising sea level (Figures 19 and 20). This spatial change at Kwelekwele Island was quantified using GIS to give the area change results in Table 12.

Overall results from the Douala Estuary mangrove GIS study (Zouh, 2010) showed that, although this offshore mangrove island used to be nine times larger in 1975 than what remains 35 years later, the majority of mangroves of the estuary have shown little change in area in the last 20 years.

Investigation of ground surface elevations within the Douala Estuary later found that ground surfaces under *Rhizophora* mangroves on Kwelekwele Island were at least 35 cm lower in elevation than the seaward edge

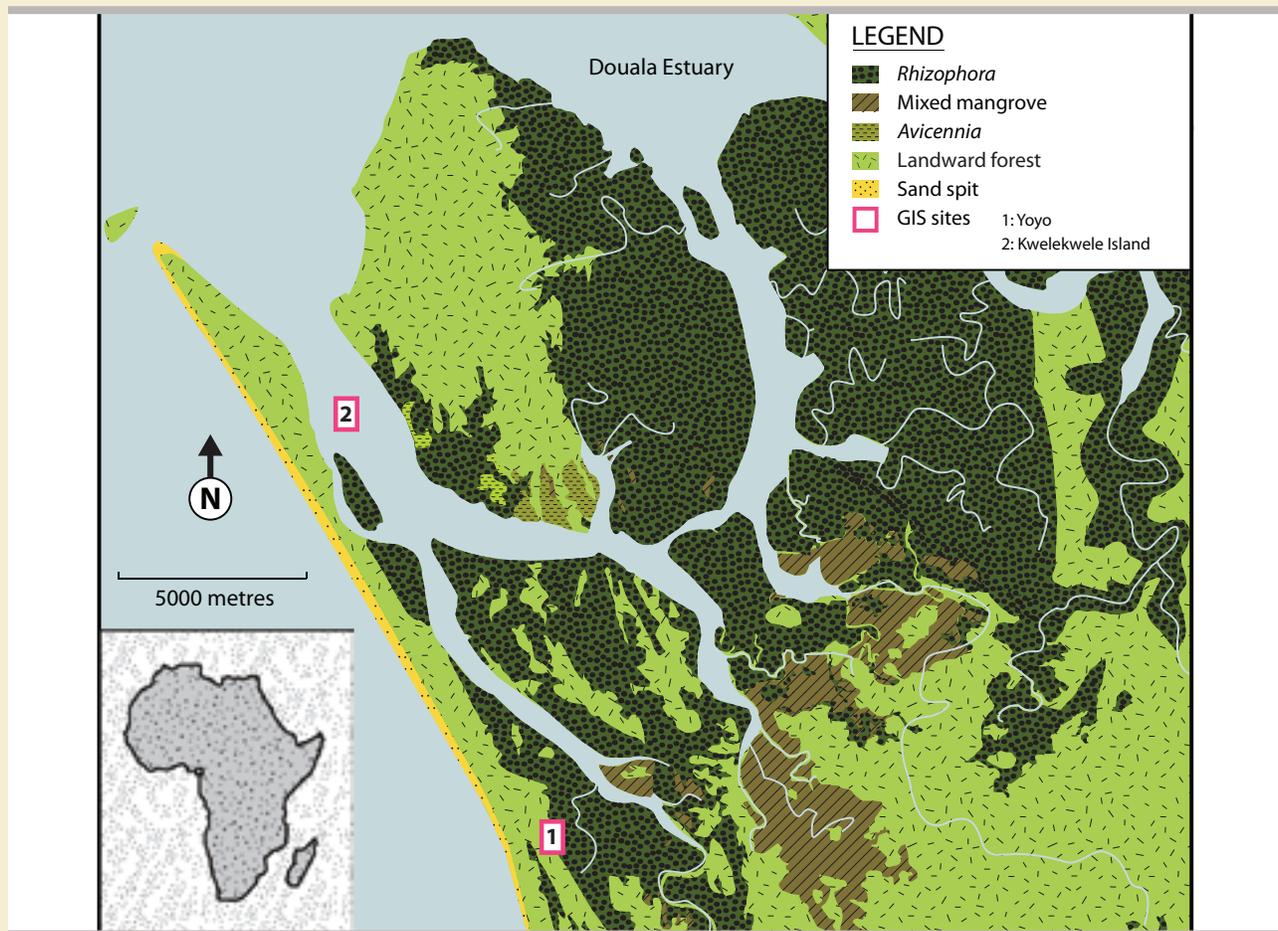


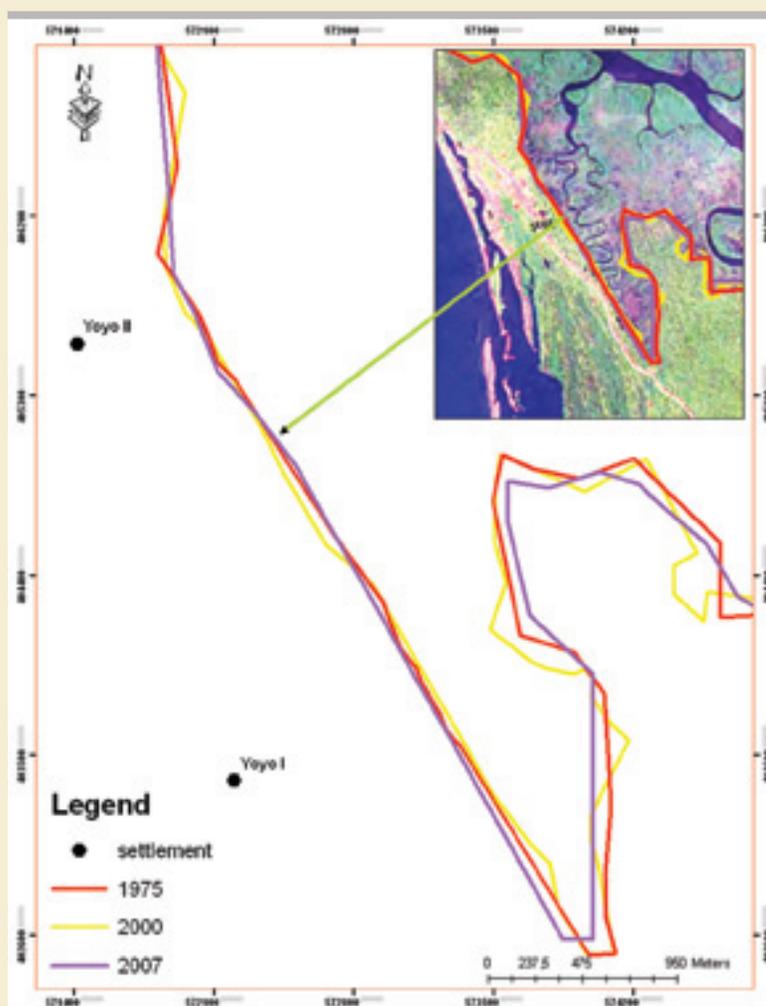
Figure 17. Douala Estuary mangrove area (adapted from Ellison & Strickland, 2010a) showing GIS study sites.

By Michael Helman

Date	Image	Time interval (years)	Cumulative time relative to base (years)	Clarity of image
1975	Landsat MSS	base	base	Very clear
1986	Landsat TM	11	11	Clear
2000	Landsat ETM	14	25	Partially clouded
2007	Landsat ETM+	7	32	Clear but with gaps due to sensor's scan line corrector (SLC) mechanism failure on May 31, 2003
2010	(Ground-truthing)	3	35	

**Table 11. Characteristics of available satellite images used in the Cameroon case study (Zouh, 2010).**

of the main body of *Rhizophora* in the rest of the estuary (Figure 17). During the compilation of local community knowledge (subsection 3.9), interviews with older residents of nearby villages revealed that they either visited or lived on Kwelekwele Island in the late 1970s and early 1980s as it was a major fishing market for the region. Then sea level inundation and constant destruction of buildings caused the island's population to reduce gradually until there was a major inundation on the island in the mid 1980s, which finally caused the remaining population to leave (Ajonina et al., 2011). This case study demonstrates how offshore islands at the seaward edge are especially vulnerable to rising sea level owing to their lower elevation, particularly when combined with human disturbance.



**Figure 18. Mangrove landward margin change near Yoyo I and II villages, Douala Estuary, Cameroon (from Zouh, 2010). This site shows little change and hence would have a reduction in mangrove area vulnerability score = 1 (little change).**

Year	Island area (m <sup>2</sup> )
1975	39,200
1986	17,300
2000	6,900
2007	4,400
2010	4,300

Table 12. Kwelekwele Island mangrove area change, 1975 to 2010 (Zouh, 2010).



Photo: Joanna Ellison

Figure 20. Kwelekwele Island in June 2009, showing evidence of forest retreat with open trees at the island edge and lack of canopy cover descending to near water level, which is normal for seaward-edge mangroves.

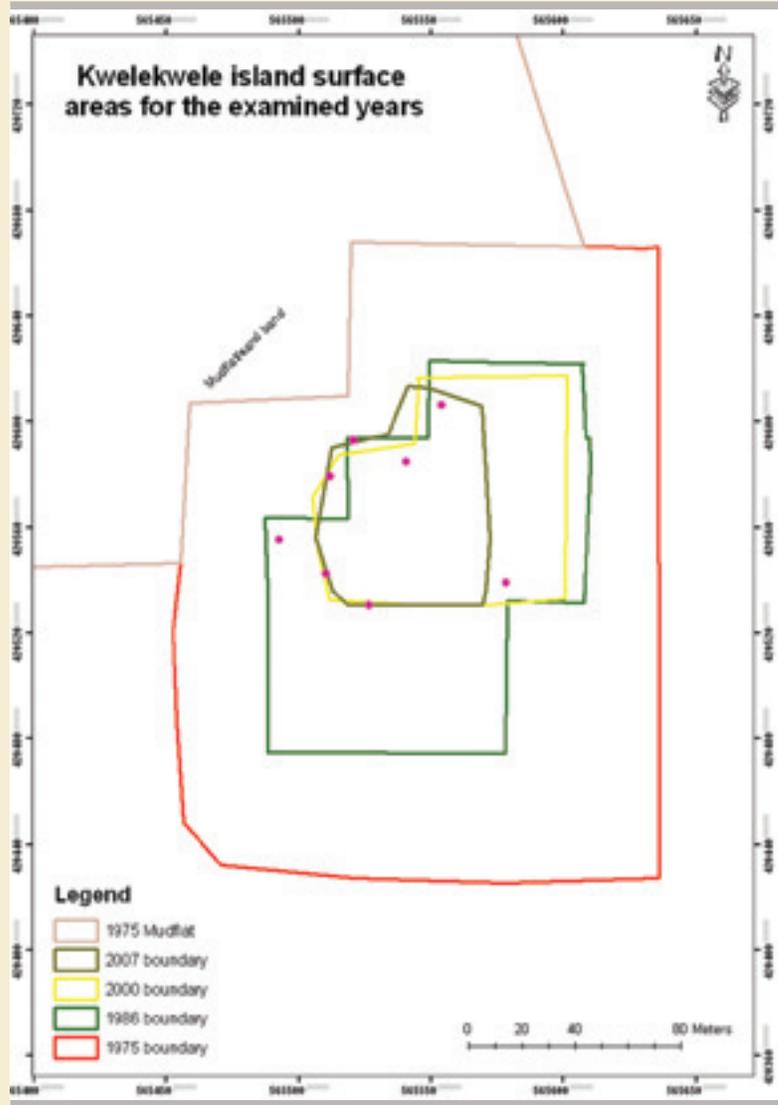


Figure 19. Seaward edge retreat of Kwelekwele Island from 1975 to 2010 (from Zouh, 2010). This site has a seaward edge retreat score = 5 (very significant change).

The overall Douala Estuary GIS vulnerability scores are:

Rank	1	2	3	4	5	S
<b>Sensitivity factors</b>						
Seaward edge retreat	None	Some	Moderate	Significant	Very significant	2
Reduction in mangrove area	None	Some	Moderate	Significant	Very significant	1

## 3.4 Ground surface elevations in and behind mangroves

Approach	Expertise/ Technology needed	Time taken	Cost	Contribution to VA
dGPS	High	Some	High	Rather high
Water level	Some	Some	Some	Rather high

### What is it?

This is a survey of ground elevations in the mangrove area and immediately to landward, preferably related to the country's mean sea level datum.

If the mangrove area and species zones are within smaller elevation brackets, this increases the mangrove area's sensitivity to sea level rise. This is mostly controlled by tidal range, which is an exposure factor (Figure 3). If there are few areas inland that are of suitable elevation for mangrove migration, this reduces adaptive capacity.

### Why do it?

Mangrove species zonation is evident in most mangroves and is controlled by elevation of the substrate or mud surface through the influence this has on inundation frequency/duration, salinity and soil oxygen levels (Watson, 1928). Because their habitat occurs between mean sea levels and high tide levels, mangroves are particularly sensitive to sea level rise. Therefore, measurement of mangrove elevations is a useful part of a vulnerability assessment. Although a mangrove area has a very low elevation range, as it occupies only half of the intertidal zone, there is a micro-topographic gradient from the seaward edge to the landward edge, and height thresholds within this gradient are preferred by different species, such as *Rhizophora* at the seaward edge and *Bruguiera* toward the landward edge (Figure 21).

The survey datum for elevation in each country is related to mean sea level. With rising sea level the inundation frequency and duration will increase, thereby changing the microhabitats of mangrove species zones. Sea level rise is one of the greatest impacts of climate change on mangroves (Table 1). Storms, rainfall changes and reduced productivity can also affect mangrove mud accretion.

Tolerance of a wider elevation bracket and of deeper water indicates more "climate-smart" or resilient mangrove species with regard to sea level rise. This can guide species selection when mangrove replanting is undertaken as an adaptation action (Section 5).

### How to collect data

Elevation of the mangrove substrate at the seaward edge and species zone transitions within the mangrove area and at the landward edge can be determined using a number of methods from low-technology (English et al., 1997) to high-technology, or a combination of both. These methods are described in the following subsections. Elevation surveys are best related to the country's mean sea level datum, as used by permanent survey benchmarks and the datum of any tide gauge. This datum provides an accurate elevation against which changes such as rising sea level are measured.

### 3.4.1 High-technology methods

Handheld GPS units are not useful for elevation surveys, as the vertical error of these units is too great to distinguish the small vertical differences within mangroves. Differential GPS (dGPS) and electronic distance meters (EDM) are high-technology ground techniques that give good vertical accuracy. Both dGPS and EDM involve a tripod-mounted receiver or electronic level that relates to a mobile rover pole or reflector that is moved around the survey site.

Differential GPS (dGPS) determines the difference in position between a GPS rover receiver on a position within the mangroves and another tripod-mounted GPS receiver at a known survey point. These receivers do not need line of sight to each other, but do require a fairly clear view of the sky. This technique

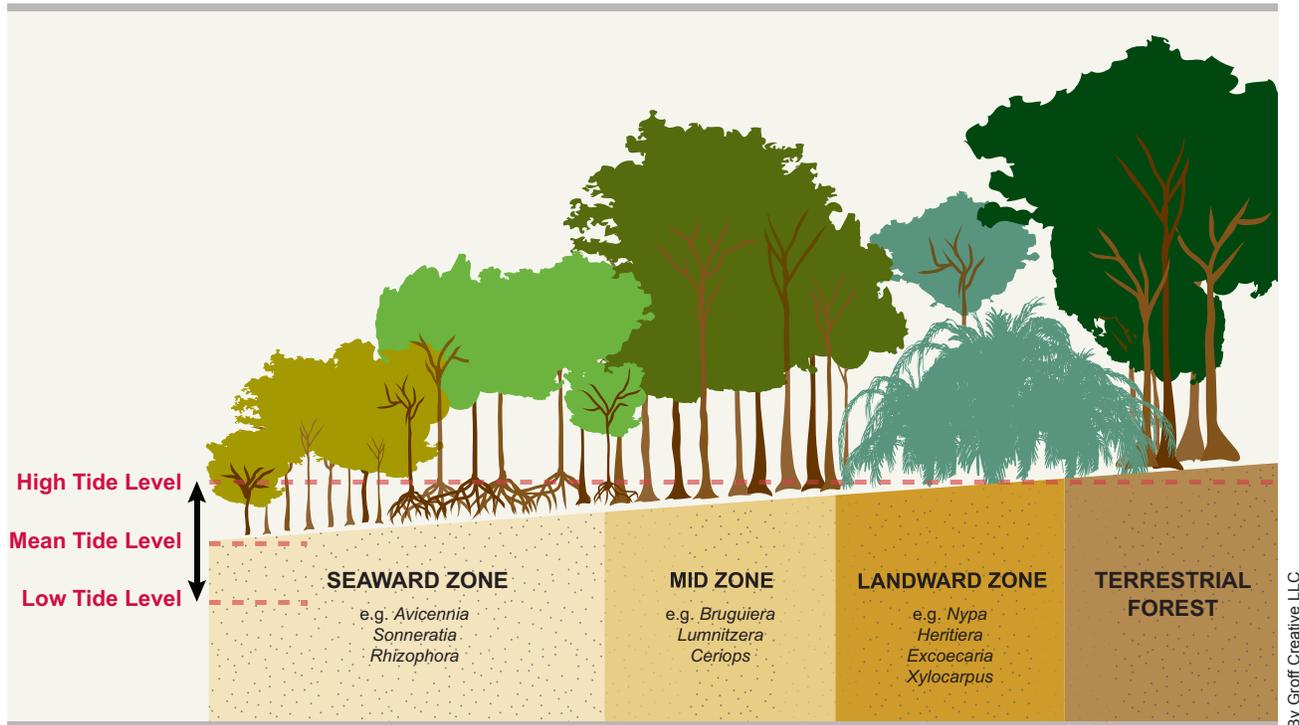


Figure 21. Mangrove species zonation by elevation and inundation frequency (adapted from Ellison, 2009a).

requires sophisticated GPS receivers, typically costing US\$20,000 or more each and experienced surveyors.

Conventional tripod-mounted survey levels/theodolites or electronic distance meters (EDM) are the standard technique of qualified surveyors. They need line of sight to each other, which is difficult within mangrove forests. Like dGPS, this technique requires specialized equipment but also professional surveying staff who are often more accustomed to working in dry land environments.

LiDAR (Light Detection and Ranging) is an active laser scanning system deployed from aircraft to obtain high-resolution, accurate topographic data. The data is vertically accurate to 15 cm (Whitman et al., 2003), and resolution and swath width depend on the height of the plane (a lower-flying plane provides higher-resolution elevation data but a narrower swath width). Ground elevation data can be obtained through vegetation by LiDAR. Because of the specialized equipment and expert personnel needed, LiDAR data are very expensive to gather (Rubens et al., 2011), as indicated by price quotes for the Tanzania WWF pilot area of at least US\$200,000. Because the technique is

more commonly used in highly capitalized industries such as mining or hydropower development, relevant local stakeholders may already have data that could be obtained by a vulnerability assessment project.

If the VA's resources and partnerships permit the use of dGPS or EDM techniques, use the transects surveyed in subsection 3.2 to survey the average mud level at each observation point, including the seaward and landward edges as described in the following subsection on low-technology methods.

The elevation to measure is the average mud surface level inside the mangroves, the level that is influencing tidal inundation frequency experienced by the trees. If sophisticated techniques are used, surveyors should make sure that survey staffs or reflector poles do not sink into the mud at their base. If they sink into the mud, they will record a lower elevation than actual. One way to prevent this is to place a thin plastic lid on the mud surface below the pole.

Advantages and disadvantages of these sophisticated methods for elevation survey in and behind mangroves are summarized in Table 13.

Method	Advantages	Disadvantages
1. Ground survey using differential GPS (dGPS)	<ul style="list-style-type: none"> <li>• very high level of vertical resolution (&lt;5 cm)</li> <li>• flexible — can be targeted to include/exclude specific areas</li> <li>• equipment expensive but can be hired relatively cheaply compared to remote methods</li> <li>• mangrove project staff deployed on the rover pole gives good ground-truthing</li> </ul>	<ul style="list-style-type: none"> <li>• involves on-the-ground fieldwork and so can be time-consuming and costly for large areas</li> <li>• requires regular battery charging in remote rural areas</li> <li>• difficult to use under forest canopies</li> </ul>
2. Ground survey using laser theodolite (EDM)	<ul style="list-style-type: none"> <li>• uses surveying equipment commonly held in survey departments and companies</li> <li>• stakeholders such as government lands department likely to have equipment and expertise</li> <li>• high level of vertical resolution</li> <li>• mangrove project staff deployed on the reflector pole gives good ground-truthing</li> </ul>	<ul style="list-style-type: none"> <li>• requires line of sight survey, which is difficult in forests</li> <li>• requires regular battery charging in remote rural areas</li> <li>• needs to refer to ground datum that may be far from study area</li> </ul>
3. Photogrammetry (3D aerial photography)	<ul style="list-style-type: none"> <li>• relatively cost-efficient for very large areas</li> </ul>	<ul style="list-style-type: none"> <li>• costly in absolute terms</li> <li>• not suitable for areas with relatively high vegetation cover</li> <li>• cloud cover problematic</li> <li>• expertise and equipment difficult to obtain</li> </ul>
4. LiDAR (Light Detection and Ranging)	<ul style="list-style-type: none"> <li>• higher level of accuracy and more information than aerial photography (&lt;8 cm)</li> <li>• records tree height as well as ground height under trees</li> <li>• relatively cost-efficient for large areas</li> </ul>	<ul style="list-style-type: none"> <li>• higher cost even than 3D photogrammetry</li> <li>• expertise and equipment difficult to obtain</li> </ul>

**Table 13. Summary of high-technology methods for elevation survey (adapted from Hemed & Mbegha, 2009; Rubens et al., 2011).**

An example of a survey using dGPS and a list of equipment used by the surveyors are provided in the Tanzania case study that follows.

**How to interpret vulnerability**

Rank vulnerability on the scale below. Record each score in the final column (S = score).

Rank	1	2	3	4	5	S
<b>Exposure factors</b>						
Tidal range	>3 m	2-3 m	1.5–2.0 m	1–1.5 m	<1 m	
<b>Sensitivity factors</b>						
Elevations within mangroves	Zone brackets 60 cm +	Zone brackets 50–60 cm	Zone brackets 30–50 cm	Zone brackets 20–30 cm	Zone brackets <20 cm	
<b>Adaptive capacity factors</b>						
Elevations above mangroves	Migration areas very available	Migration areas mostly available	Some migration areas available	Few migration areas available	No migration areas available	

### Case study: Tanzania – high-technology differential GPS

The micro-elevation of areas above the highest high tide mark inland of the North Rufiji Delta mangroves in Tanzania was surveyed using differential GPS to assess the potential for migration of mangroves inland in response to sea level rise (Kimeu & Machano, 2011).

The fieldwork for this study was done in two sessions. The dGPS survey of the points above the highest high tide mark took 12 days, and a second field session of four days linked the first survey base points with the national datum using a known triangulation point.

#### How to collect data

Adjacent to the survey area, a base point was established by picking a random area clear of trees; and subsequent bases were points that linked to the main base, using Real Time Kinematic (RTK) receivers. The base points were set in open fields to avoid refraction rays due to vegetation or structures that can distort accuracies (Figure 22). For each base point, a fast static survey was carried out with occupation duration of one hour to establish the absolute XYZ coordinates of the base point.

RTK systems use a single base station receiver (Figure 22a) and a number of mobile units called rovers (Figure 22b). The base station rebroadcasts the phase of the carrier that it measured, and the rovers compare their own phase measurements with the ones received from the base station.

There are several ways to transmit a correction signal from base station to mobile station. The most popular way to achieve real-time, low-cost signal transmission is to use a radio modem, typically in the UHF band. In most countries, certain frequencies are allocated specifically for RTK purposes. Most land survey equipment has a built-in UHF band radio modem as a standard option. This allows the units to calculate their relative position to millimeters, although their absolute position is accurate only to the same accuracy as the position of the base station. The typical nominal accuracy for these dual-frequency systems is  $1 \text{ cm} \pm 2 \text{ ppm}$  horizontally and  $2 \text{ cm} \pm 2 \text{ ppm}$  vertically. This accuracy can go as high as 2 mm in plane and 4 mm for elevation depending on the system, duration of point occupation, and distance of the rover from the base station.



Figure 22. The RTK system, composed of (a) setting a base station by static surveying (left), and (b) RTK mode with both base (left) and rover (right) working together (Kimeu & Machano, 2011).

### Equipment Required

#### Base set

- Base receiver
- Geodetic antenna
- Tripod
- Tribrach and carrier support
- Measuring tape
- Base antenna cable
- External 1000mAh battery
- Personal safety gear

#### 2 rover sets

- Rover receivers (2)
- Antenna
- Antenna cables
- RTK poles
- TSC2 controllers
- Controller clamps
- Personal safety gear

#### Radio

- Radio
- Radio antenna
- Radio antenna cable
- Radio antenna mounting pole
- Car battery

In Tanzania, surveying to get elevation data was done along transects separated by 100 m across the study area (Figure 23), with points located every 10 m along the transect (Kimeu & Machano, 2011). Available georeferenced satellite images aided the generation of guide coordinate points that were loaded into the survey controller prior to the survey. These control points were then linked to the survey each day and acted as a guide along which the surveyor walked and staked the points. Surveyors leveled the pole bubble before point occupations and made sure that they supported the rover weight when soil was easily penetrable in order to reduce errors caused by the pole sinking into the ground. Outlier sampling points like anthills and ditches were avoided to ensure a good representation of the ground's general elevation.

Rovers were initialized for RTK rover surveys and began receiving base corrections immediately. The receivers communicated continuously with the base, indicating when they were fixed (receiving base correction) and when they were floating (only collecting autonomous data). They were also set to

record fixed data only and with occupation times lasting a minimum of three seconds.

New base setup points were established by prior measurements, using RTK and clear marking on the ground. Several base points were used for entire surveys to keep the baselines short as well as to deal with difficulties in accessing the survey area.

#### How to analyze results

Data were downloaded daily using Trimble business center software. This was then loaded to the GIS to assess that day's performance in terms of coverage, to identify the area to be surveyed the following day and to prepare staking points. The point elevations consistency with the general slope directions were checked and found to be in conformity.

Raw data from the GPS units were corrected for the reference datum by using heights of the low tides and high tides taken on March 30, 2010, at 10:41 a.m. and 2.44 p.m., respectively, at Simbauranga and fixed to the national tide datum. References to levels of the highest high tides were also made in the areas at the back of mangroves, based on the communities' observations of where the water level reached during such tides.

The study area (Figures 23 and 24) was selected as a typical area of land adjacent to the landward mangrove margin and high tide mark, confined to a contour of 1 m elevation above existing high tides – an area that would be expected to be inundated in the event of sea level rise. The area was level with a generalized slope of about 1 m rise across 500 m. The dominant vegetation was grasses of various species, scattered shrubs, and small trees up to 2 m. These were sometimes dense to the point of blocking the GPS reception. The area was in the vicinity of some of the sites replanted with mangroves under the adaptation component of the project (see Section 5). Vegetation categories seaward of the study area included mangrove (*Heritiera sp.* and *Rhizophora/Xylocarpus/Ceriops/Avicennia*), rice farms and bare saline areas. Of the total area surveyed on the upper north delta, only 71.1 ha (8 percent) was below the highest high tide mark, while the rest (749.7 ha, equivalent to 92 percent) was above the highest high tide mark (Figure 24).

The elevation survey generated a series of maps showing inundation under projected sea level rise

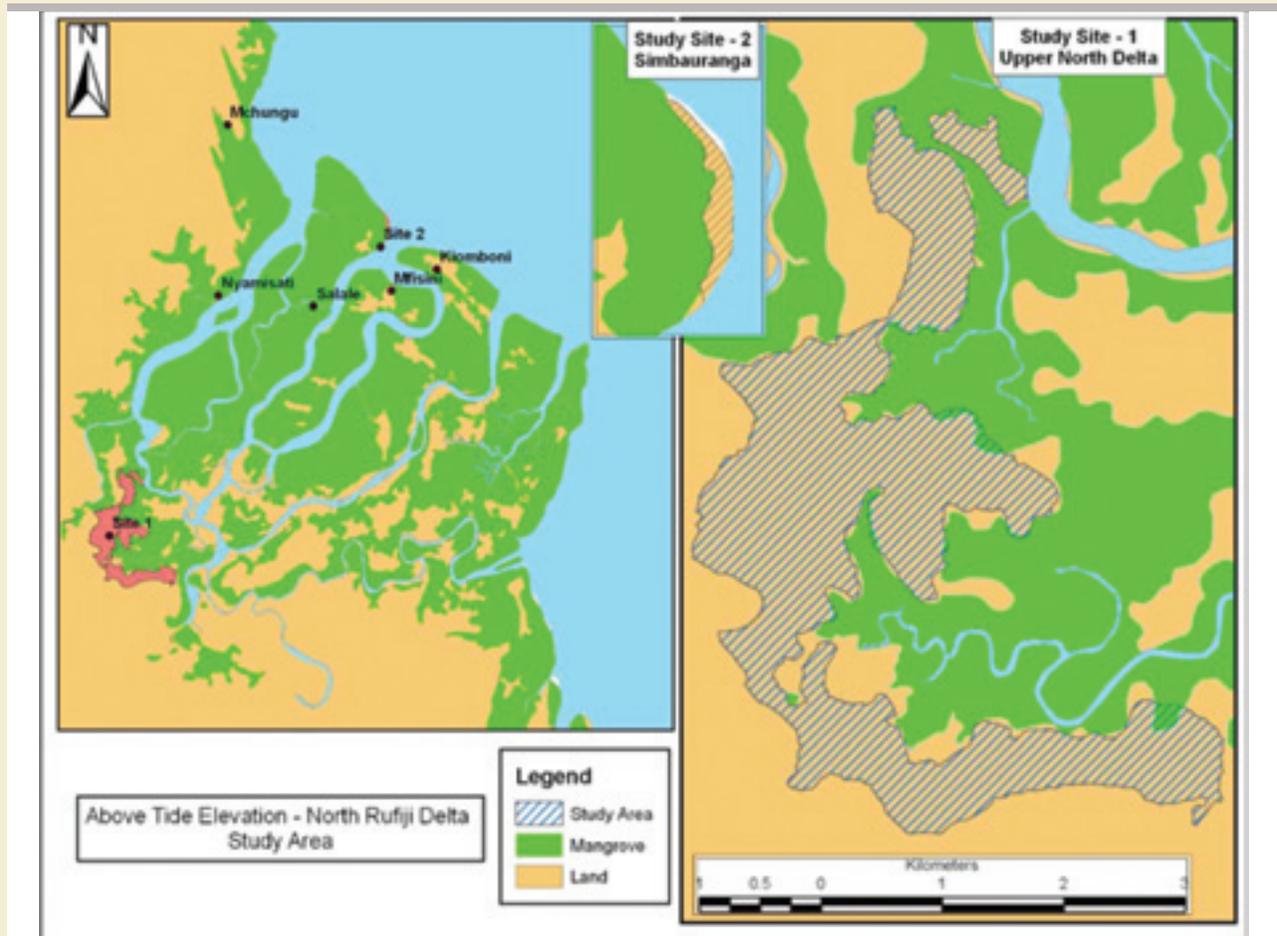


Figure 23. Location of study sites for micro-elevation survey in North Rufiji Delta (Kimeu & Machano, 2011).

scenarios of 10 cm increments up to 1 m (Figure 24) for a study area of 821 ha (Figure 23).

Raw elevation results from the central section of the study area (Figure 23) are shown in Figure 24. Highest high water was determined to be 3.7 m above tidal datum, and this elevation was used to calculate future inundation scenarios for sea level rise at 10 cm increments (Figure 25). Such future elevation scenarios are shown by the 3.8 to 4.7 m color bands in Figure 24 which show these inundation positions, assuming no sediment surface elevation change. The results, however, assist in planning for future inland migration areas (see Section 5).

#### Strengths/weaknesses

In RTK surveys, both base set and rovers require a clear view for accurate readings. The survey was thus limited to the open areas behind the mangroves. Kimeu and Machano (2011) avoided taking readings very close to high-canopy areas in the mangroves and in terrestrial vegetation, so the readings in these areas were not accessed. With this limitation, the surveyors could not properly map the highest high tide areas within the mangroves. The area covered in this study can thus be better described as the landward edge of mangroves, rather than the highest high tide area.

Due to a lack of data for the area between the mangrove edge and the channels, Kimeu and Machano

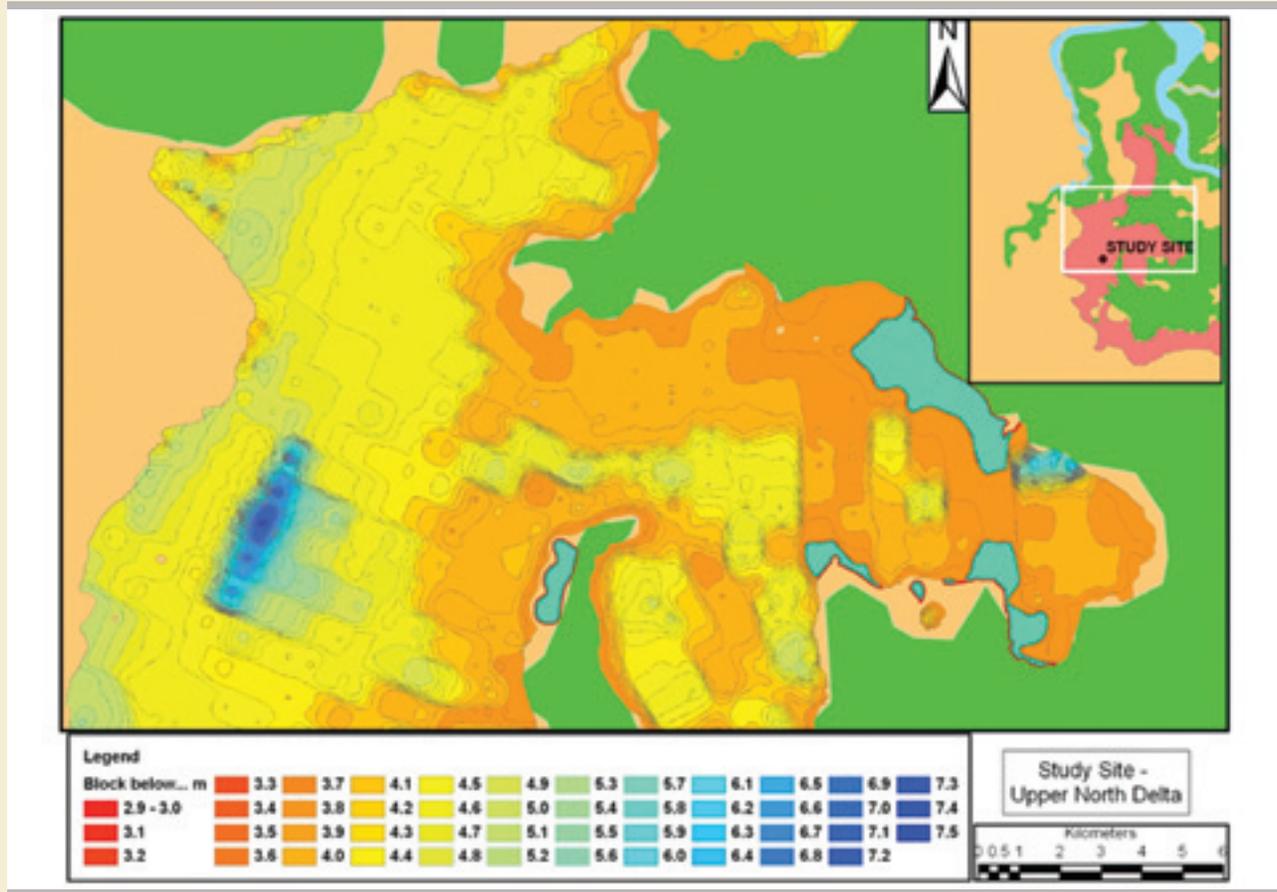


Figure 24. Raw elevation results from differential GPS survey of the central section of the North Rufiji Delta inland mangrove study area (Kimeu & Machano, 2011).

subjectively extrapolated the elevation of this area in order to get clear representation of the contours as one approaches the mangrove edge. These extrapolated elevations considered the observed characteristic inclination of the area.

**How to interpret vulnerability**

Results (Figure 24) showed that there are low-gradient areas above the current locations of mangroves into which mangroves could migrate with rising sea level. Hence this site received the following scores:

Rank	1	2	3	4	5	S
<b>Exposure factors</b>						
Tidal range	>3 m	2–3 m	1.5–2.0 m	1–1.5 m	<1 m	1
<b>Sensitivity factors</b>						
Elevations within mangroves	Zone brackets 60 cm +	Zone brackets 50–60 cm	Zone brackets 30–50 cm	Zone brackets 20–30 cm	Zone brackets <20 cm	–
<b>Adaptive capacity factors</b>						
Elevations above mangroves	Migration areas very available	Migration areas mostly available	Some migration areas available	Few migration areas available	No migration areas available	1

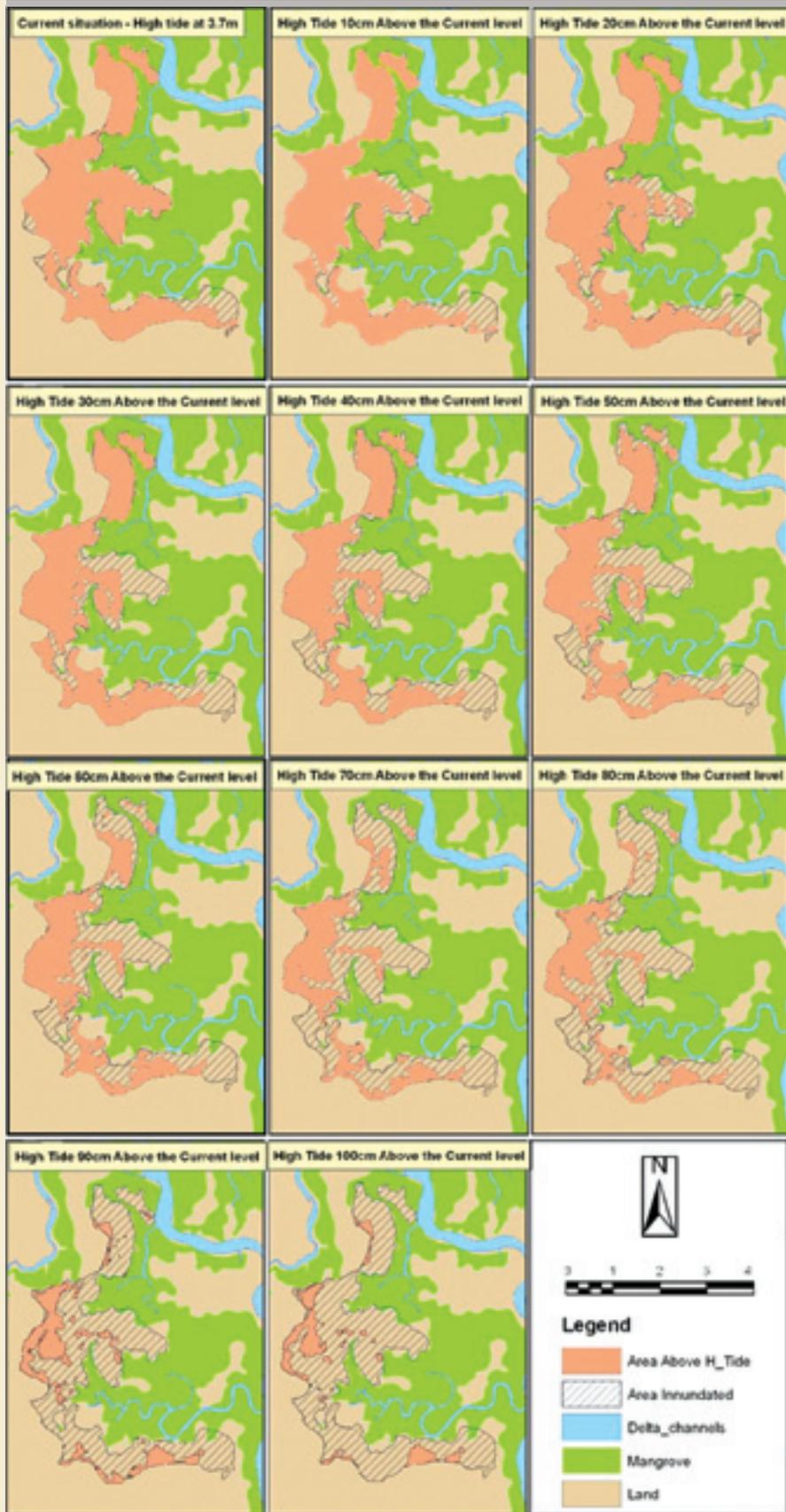


Figure 25. Inundation scenarios for projected sea level rise at 10 cm intervals up to 1 m (Kimeu & Machano, 2011).

### 3.4.2 Low-technology methods

If sophisticated high-technology survey techniques are not available or affordable, a low-technology approach can provide elevation information with acceptable accuracy, if done carefully.

Although high-technology methods such as dGPS are preferable, topographic elevation can be quantitatively described with respect to tidal range using a low-technology water level method (Figure 26). The fundamental principle of this technique is that water level is level during the latter half of rising tides. Hence the corresponding depth beneath water level can help to calculate the relative elevation of the mangrove mud surface. A rising tide is best for this approach as it has been shown that water surfaces on the flood tide are horizontal and, while on the ebb, tend to decline slightly seawards (Healey et al., 1981).

Figure 26 shows a mangrove forest in profile, with species A (i.e. *Avicennia*) at the seaward zone, R (i.e. *Rhizophora*) just inside this and B toward the landward edge (which in Tanzania and Fiji was *Bruguiera*, and in Cameroon was *Laguncularia*). Arrows show the sample design for a water level elevation survey.

In Figure 26, h is the reference station and d1, d2, d3, d4, etc. are different locations within the mangroves at which to measure mud surface elevation. Most critical for purposes of the VA are zone transitions.

#### How to collect data

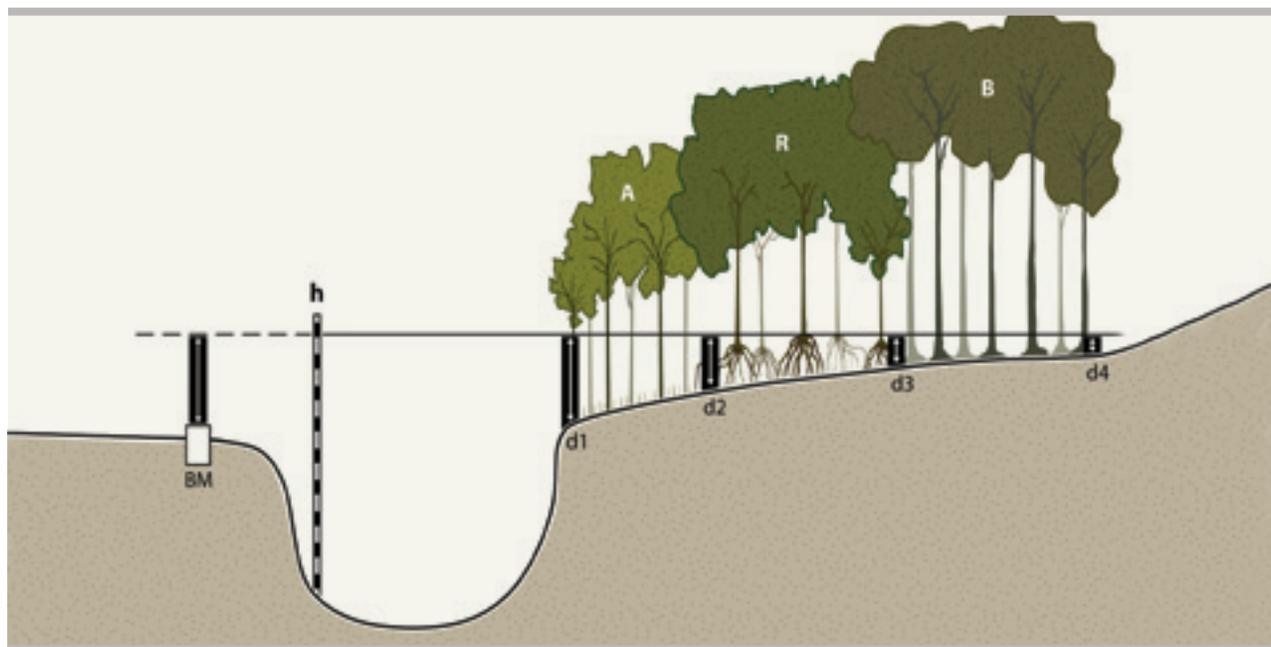
##### Equipment Required

##### Reference station (h)

- Survey stake graduated in mm with 0 at the base
- Clear plastic tube cut from a drink bottle to go over the stake
- Accurate source of time, such as mobile phone
- Communication with rover (preferable but not necessary)
- Pencils and copies of data sheets (in Appendix)
- Personal safety gear

##### Rover (d)

- Stiff measure graduated in mm (roll-up builders' metal tapes are good)
- Accurate source of time, such as mobile phone
- Communication with reference station (preferable but not necessary)
- Pencils and copies of data sheets (in Appendix)
- Personal safety gear



By Michael Heiman

Figure 26. How to use water level to determine elevation of mangrove species zones.

At least two fieldwork groups are needed – one measuring at the reference station (h in Figure 26), and a second rover group moving around the mangrove area, measuring at locations d1, d2, d3, etc.

The reference station should be located close to the mangrove area, toward the seaward edge where it is influenced by tidal levels, rather than up a river where water levels may be affected by river discharge. Use a graduated stake and place it vertically with 0 at the base. Figure 27 shows an example from Fiji using a survey stake and tape measure. Place it onto a secure point such as a mark on a concrete step to form a temporary benchmark (BM in Figure 26) that can later be surveyed to datum (see Strengths/weaknesses section).

To measure water level, read the stake in millimeters at the water level. If wind or waves are causing water level to go up and down, then slip a clear plastic tube over the top of the stake and hold this at water level to stop the water movement inside. A 1.25 litre clear plastic water bottle with the top and base cut off works well.

Sample sites for the rover (d1, d2, etc., in Figure 26) in the mangrove forest to record are:

- d1 the seaward edge
- d2 transition between seaward species zone and the next landward zone
- d3 transition between species zones within the mangrove area (*add more as required*)
- d4 transition between mangrove area and the landward edge with non-mangrove species.

If stratigraphic coring is being undertaken to reconstruct relative sea levels as part of the VA (see subsection 3.5), then the ground level of the top of each core should also be surveyed for relative elevation.

Note that the upper mangrove sites, such as d4, can only be measured at highest tide, while the seaward ones can be done from mid tide – so plan the fieldwork day with a rising tide, moving from seaward to landward. Where there is a mangrove survey transect established, as discussed in subsection 3.2, use that transect so the data can be related. It is best to



Photo: Brigid Morrison

**Figure 27. Reference station (h) at Lomawai, Fiji. The survey stake is vertical, secure at its base and taped to the tree branch for the survey period. The arrow shows the water depth to record at the same time depths are recorded in the mangroves.**

replicate measurements, taking several at different locations along the seaward edge, for example. The elevation to measure is the average mud surface level inside the mangroves – the level that is influencing tidal inundation frequency.

At the seaward edge ( $d_1$ ), mud levels will slope down on the edge of a creek bank; so go a few meters inside the mangrove trees where the mud levels are flatter. Also, because crab activity will cause mud level variation, look for areas that are undisturbed by crabs.

Data sheets are provided in the Appendix. The water depths in the mangroves must be recorded at the exact same time that an observer records the water depth at the reference station ( $h$ ). Depths in the mangroves can be recorded at different times by the second person/group, so long as a corresponding measurement for each is taken at the same time at the reference station. Corresponding time measurements can be communicated by radio or mobile phone, or

measurements can be taken at prearranged times, such as every 10 minutes.

Water depths should be measured in mm, using a stiff tape or survey pole held vertically in the water to the average mud level (Figure 28). If the water is deep and turbid, quickly take several measurements at different places and record an average level.

If communication is by phone or radio, the location column at the reference station can be filled out with the site where the other person is measuring, as communicated at the time by phone or radio. If regular times (such as every 10 minutes) are used for measurements, the time column should be agreed before the fieldwork starts, and watches should be checked so that they are synchronized.

Elevation surveys above tidal levels can only be done using high-technology techniques described in the previous subsection, such as dGPS or LiDAR, due to the lack of tidal water. Such elevation surveys above tidal level provide useful information for adaptation planning, as they can identify potential migration areas for mangroves with predicted relative sea level rise. A case study from Tanzania included earlier in this subsection shows the value of such surveys for adaptation planning.

#### How to analyze results

To interpret elevation ( $E$ ) of a mangrove location ( $d$ ) when measurements are taken at the same time:

$$E = h - d \text{ (for each mangrove station such as } d_1, d_2, d_3, \text{ etc.)}$$

To interpret elevation ( $E$ ) of a mangrove location ( $d$ ) when measurements are taken at different times:

$$E = h_1 - d_1 \text{ (for each mangrove station when } h \text{ and } d \text{ are both measured at the same time)}$$

It is crucial that the same ( $h$ ) survey stake is used for this calculation.

As shown in Figure 26, if the reference station ( $h$ ) can be related to the mean sea level (MSL) of the local survey datum, elevation results can be described



Photo: Gordon Ajonina, Cameroon Wildlife Conservation Society

**Figure 28. Recording water depth at sample sites ( $d$ ) within the mangroves at the same time as a measurement is taken at the reference station ( $h$ ).**

relative to MSL. A government surveying department may be willing to help out with this task for half a day, as opposed to doing the whole survey. If this is possible, then leave the reference station (h) securely in place until the surveyors can do the work.

**How to interpret vulnerability**

Mangrove zones that occupy a smaller elevation bracket in the tidal spectrum will be more perturbed by sea level rise than mangrove zones that occupy a wider elevation bracket. This factor increases exposure.

Mangroves that occur in a microtidal area will be more perturbed by sea level rise than those that occur in a macrotidal area (see Figure 3). For example, a 30 cm sea level rise would totally relocate the intertidal zone upslope in a 30 cm tidal range, such as in the Caribbean, but only move it by less than 50 percent in a 3 m tidal range, such as in Tanzania. This factor increases exposure.

In conditions of rising sea level, mangrove areas may need to migrate inland. If this is not possible, the vulnerability of the ecosystem increases. Where there is hard development immediately inland that includes incompatible land uses (e.g. intensive farming, settlements, infrastructure), this makes inland migration very difficult and increases vulnerability. Vulnerability also increases where steep topography limits the opportunity for inland migration of mangroves.

Rank vulnerability on the scale below. Record each score in the final column (S = score).

**Strengths/weaknesses**

The best universal coverage of an area is obtained using more sophisticated techniques (Table 13). However, this can be prohibitively expensive and requires specialist consultants. Cost is declining over time as these technologies become more widely used and the equipment is manufactured more efficiently.

Fairly accurate results can be obtained using the water level technique, if done carefully, only on a rising tide, and related to tidal datum. Relating to tidal datum may require help from a surveyor using sophisticated techniques, but this can be done quickly and as a dry land task. Surveyors with expensive electronic equipment often dislike wet, muddy, tree-covered fieldwork sites, whereas relating the reference point to datum would be normal work for such specialists.

Rank	1	2	3	4	5	S
<b>Exposure factors</b>						
Tidal range	>3 m	2–3 m	1.5–2.0 m	1–1.5 m	<1 m	
<b>Sensitivity factors</b>						
Elevations within mangroves	Zone brackets 60 cm +	Zone brackets 50–60 cm	Zone brackets 30–50 cm	Zone brackets 20–30 cm	Zone brackets <20 cm	
<b>Adaptive capacity factors</b>						
Elevations above mangroves	Migration areas very available	Migration areas mostly available	Some migration areas available	Few migration areas available	No migration areas available	

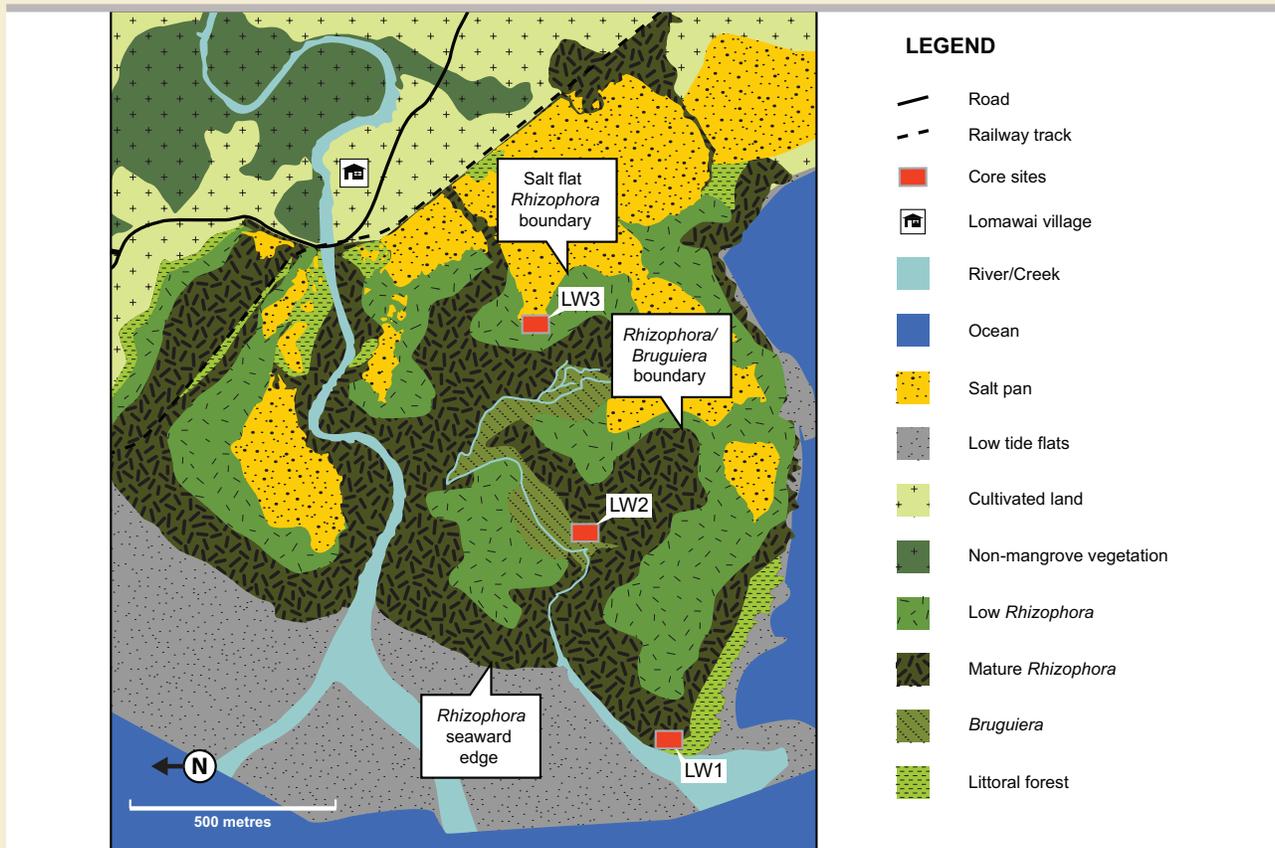
### Case study: Fiji – low-technology water level elevation survey

In Fiji’s Lomawai Reserve, the water level technique was used to measure elevations of both mangrove species zones and the stratigraphic core locations described in subsection 3.5. Results showed that distinct mangrove zonation corresponding with micro-elevation were found within the reserve (Figure 29) with tall *Rhizophora* forests dominating the seaward edge from 1.9 to 2.6 m below elevation datum, a range of around 0.7 m (Table 14).

At the time of this fieldwork, benchmark information was not available, and the study was related to a secure point along a nearby railway line (Figure 29). This was later surveyed to datum using differential GPS by the Fiji government’s Department of Lands, Division of Surveyors (Figure 30).

Zone or core location	Elevation (m)
LW3 core top	0.73
Salt flat/ <i>Rhizophora</i> boundary	0.66
<i>Rhizophora</i> / <i>Bruguiera</i> boundary	0.36 +/- 0.1
LW2 core top	0.23
LW1 core top	0.22
<i>Rhizophora</i> seaward edge	-0.34 +/- 0.1

**Table 14.** Elevations of mangrove zones in the Lomawai Reserve, in meters relative to mean sea level (MSL) datum.



**Figure 29.** Map of the Lomawai Reserve, Fiji, showing mangrove zones and location of core sites (from Ellison & Strickland, 2010b).

By Michael Helman



Photo: Rob Anders

**Figure 30. Surveying a temporary benchmark to datum using differential GPS, Lomawai, Fiji.**

*Bruguiera*-dominant forests were found more inland, at and above 0.3 m above MSL, and stunted *Rhizophora* occurred above this toward the salt flat/mangrove boundary, which was at 0.66 m above MSL. The survey results indicate an elevation range of 1.0 +/- 0.1 m for mangroves in the Lomawai Reserve. The species with the widest elevation range was found to be *Rhizophora stylosa* at -0.34 to 0.73 m, which is a range of about 1 m. This shows that *Rhizophora* is more tolerant of differences in inundation regime.

In rising sea level conditions, this species is more “climate-smart” than *Bruguiera*, which had a more restricted elevation range.

Inland from the mangroves, there are salt flats onto which mangroves could migrate; however, a railway line and village development would block mangrove migration further inland.

Hence this site received the following scores:

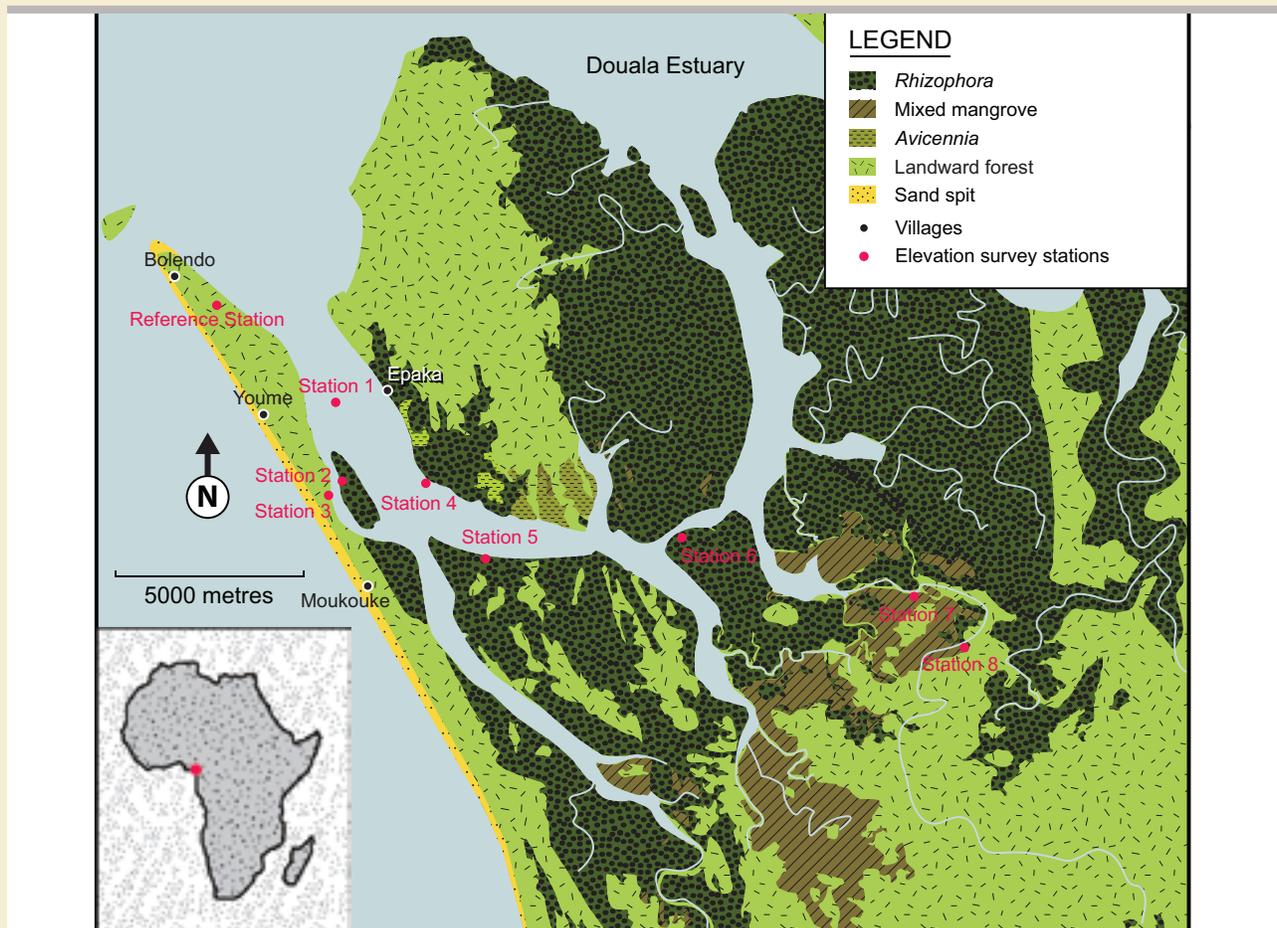
Rank	1	2	3	4	5	S
<b>Exposure factors</b>						
Tidal range	>3 m	2–3 m	1.5–2.0 m	1–1.5 m	<1 m	4
<b>Sensitivity factors</b>						
Elevations within mangroves	Zone brackets 60 cm +	Zone brackets 50–60 cm	Zone brackets 30–50 cm	Zone brackets 20–30 cm	Zone brackets <20 cm	3
<b>Adaptive capacity factors</b>						
Elevations above mangroves	Migration areas very available	Migration areas mostly available	Some migration areas available	Few migration areas available	No migration areas available	3

### Case study: Cameroon – low-technology water level elevation survey

Through one day of fieldwork, a transect across the Douala Estuary mangrove area was surveyed for elevation using the low-technology water level technique (Figure 28 and Ajonina, 2011). The sites selected (Figure 31) were at the seaward edge, including the eroding Kwelekwele Island (Figure 20; see case study in subsection 3.3).

Results, shown in Table 15, indicate that the range of mangroves is from 6.75 to 75.4 cm, about a 70

cm elevation bracket in a tidal range of 1.2 m. It is normal for mangroves to occupy the upper half of the tidal range. Kwelekwele Island is about 35 cm lower than mangrove areas elsewhere in the estuary at the seaward edge, and this contributes to its vulnerability (Figure 20 and Table 12). *Rhizophora racemosa* has the broadest elevation range, about 6 to 54 cm, which would make it the most “climate-smart” species of those present. *Laguncularia*, in particular, and *Avicennia* have narrower elevation brackets, making them less able to tolerate rising sea levels.



By Michael Helman

Figure 31. Douala Estuary mangrove area showing elevation survey sites.

Station	Location	GPS location	Mangrove zone	Elevation (cm)
Reference station	Jonathan Creek	03° 48' 01.9" N; 009° 34' 04.4" E	Seaward of mangroves	0
1	Kwelekwele Island	03° 48' 17.6" N; 009° 35' 24.0" E	<i>Rhizophora racemosa</i>	6.75
2	Moukouke core site 1	03° 45' 54.9" N; 009° 35' 40.4" E	<i>Rhizophora</i>	47.0
3	Seaward	03° 45' 27.5" N; 009° 35' 37.6" E	<i>Rhizophora</i> and <i>Avicennia</i>	44.4
4	Seaward	03° 45' 35.1" N; 009° 37' 09.0" E	<i>Avicennia</i>	21.3
5	Middle	03° 44' 31.9" N; 009° 37' 52.6" E	<i>R. mangle</i>	75.4
6	Nkamba core site 2	03° 44' 46.7" N; 009° 40' 41.42" E	<i>R. racemosa</i>	54.1
7	Landward	03° 43' 58.6" N; 009° 44' 02.2" E	<i>Laguncularia</i> with some <i>Raphia</i> palms	73.1
8	Landward	03° 43' 05.6" N; 009° 45' 09.0" E	Freshwater swamp	75.2

Table 15. Elevation of mangrove substrate surface in the Douala Estuary mangrove area (adapted from Ajonina, 2011).

The results in Table 15 show most mangrove zones to be in elevation brackets of a low range: 30 to 50 cm, even less for some species. The tidal range is only slightly over 1 m. There are inland migration areas

available at suitable low elevations, but other land uses are prevalent there for now. This site therefore received the following scores:

Rank	1	2	3	4	5	S
<b>Exposure factors</b>						
Tidal range	>3 m	2–3 m	1.5–2.0 m	1–1.5 m	<1 m	4
<b>Sensitivity factors</b>						
Elevations within mangroves	Zone brackets 60 cm +	Zone brackets 50–60 cm	Zone brackets 30–50 cm	Zone brackets 20–30 cm	Zone brackets <20 cm	3
<b>Adaptive capacity factors</b>						
Elevations above mangroves	Migration areas very available	Migration areas mostly available	Some migration areas available	Few migration areas available	No migration areas available	3

## 3.5 Relative sea level trends

Approach	Expertise/ Technology needed	Time taken	Cost	Contribution to VA
Tide gauge data <sup>1</sup>	Moderate	Some	Low	High
Stratigraphy/pollen analysis	Rather high	Rather high	Rather high	Moderate-High <sup>2</sup>

### What is it?

Establishing the long-term relative sea level trends of the site helps to understand the net sea level change to be expected in combination with global sea level rise.

The rate of relative sea level rise is an important exposure factor for mangrove systems. Stratigraphic coring studies also provide data on long-term sedimentation rates, which is a key sensitivity factor for mangroves. This topic is covered in subsection 3.6.

### Why do it?

Changes in sea level can result from variation in the volume of ocean water or adjustment movement of the land, continental shelf or ocean floor (Figure 32). A coastal location will experience relative sea level change or stability owing to a combination of these factors. Some coastal areas experience long-term relative sea level rise owing to tectonic subsidence, sediment compaction or fluid extraction (Syvitski et al., 2009; Nicholls & Cazanave, 2010). Recent and projected sea level rise, mainly caused by expanding oceans and melting ice, is adding to this phenomenon. Sites with deltaic subsidence, such as Louisiana in the United States and the Ganges-Brahmaputra delta in India and Bangladesh, are more exposed (Desantis et al., 2007; Nicholls & Cazanave, 2010), while those with tectonic uplift are less exposed (Nicholls & Lowe, 2004; Nicholls & Cazanave, 2010). Such relative sea level trends can be tracked us-

<sup>1</sup> Refers just to use of the data, not the setup and maintenance of a tide gauge – which is high-technology, expensive and requires lengthy data sets.

<sup>2</sup> Some sites can be difficult to interpret; others are easy.

ing long-term tide gauges (Bindoff et al., 2007). However, many mangrove coastlines in the developing world lack such records.

### How to collect data

Two alternative approaches are outlined. The best is use of local tide gauge data where this is available; otherwise, a proxy method is described for reconstruction of past sea levels from stratigraphy.

### How to interpret vulnerability

As global sea levels rise, coastal areas that are subsiding will experience higher rates of relative sea level rise than areas that are stable. Such subsidence may be due to tectonic movement or deltaic compaction, isostatic adjustment and fluid extraction. This factor increases exposure.

Rank vulnerability on the scale below. Record each score in the final column (S = score).

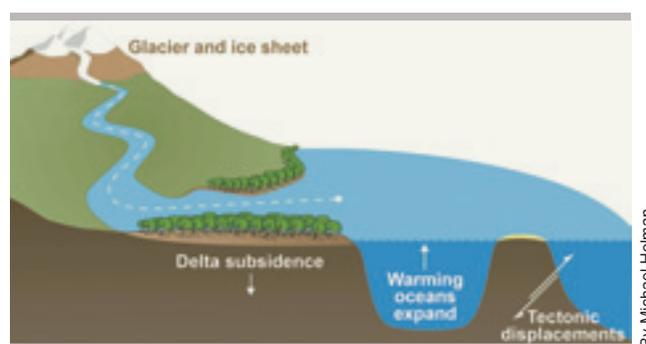


Figure 32. Causes of relative sea level change in mangrove areas.

Rank	1	2	3	4	5	S
<b>Exposure factors</b>						
Relative sea level rise (RSLR)	Site uplifting	Site slightly uplifting	Site stable	Site slowly subsiding	Site rapidly subsiding	

### 3.5.1 Tide gauges

Measurement of present-day sea level change is by two different techniques, tide gauges and satellite altimetry (Bindoff et al., 2007). Satellite altimetry data has not been collected for long enough as yet to reliably show long-term coastal change. Tide gauges provide sea level variations with respect to the coastal land on which they lie, which is the information needed for climate change vulnerability assessment in mangrove areas. As described in subsection 3.1, if there is a long-term tide

gauge for the VA location, this can be used to analyze relative sea level trends for the last few decades. The tide gauge should be located on the same section of coastline, within a few kilometers. The following case study from Singapore shows this approach. Results can be compared with global sea level trends (Bindoff et al., 2007) to show relative sea level, as explained in the data analysis section of the case study.

#### Case study: Relative sea level trends of Singapore

The VA methodology described in this manual was tested in Singapore by Holly Siow, now of the National University of Singapore (Siow, 2009). Unlike the WWF pilot sites in Cameroon, Tanzania and Fiji (Table 3), Singapore has long-term tide gauge data from close to its largest mangrove area at the Sungei Buloh Wetland Reserve (Figure 33). While tide gauge data exists for Singapore, published interpretation could not be found. Table 16 shows trends in mean annual tide gauge data for Singapore calculated from tide gauge data from the Permanent Service for Mean Sea Level (PSMSL).

An increase in sea levels was shown at all stations since the mid-1990s, with two stations closest to the mangrove study site and with longer data records at Johor Bahru and Sembawang showing 1.3 to 1.5 mm per year relative sea level rise since the mid-1990s. At the Johor Bahru station sea levels rose 1.2 mm per year since 1994 (Table 16, Figure 34). At Sembawang, sea levels rose 1.4 mm per year after 1994 (Table 16, Figure 35). Although some stations showed an overall trend of decreasing sea levels, all stations showed a trend of increasing sea levels since the mid-1990s. Apart from Jurong, these are consistent with the global trends in sea level rise of the last few decades (Bindoff et al., 2007).

Station	All years mm per year	Earlier data mm per year	Later data mm per year
Johor Bahru	1.7	-1.4	1.3
Kukup	2.3	0.8	3.3
Sembawang	-1.3	-3.4	1.5
Jurong	-1.1	-2.8	8.6
Tuas	3.5		3.5
West Coast	0.4		0.4

**Table 16. Shows relative sea level change (mm per year) from tide gauge stations near Sungei Buloh Wetland Reserve, Singapore (data from [www.psmsl.org](http://www.psmsl.org)). For Johor Bahru, Kukup and Sembawang, earlier data are from before 1993, and later data are from after 1993. For Jurong, earlier data are from 1971–1986, and later data are from 1987–1996. For Tuas, only data from 1997 to 2008 are available; and for West Coast, only data from 1998 to 2008 are available, shown in the “Later data” column. Given that these are records of less than 30 years, however, they can only be taken as indicative.**

Figures 34 and 35 show variability in sea levels, which can be caused by atmospheric pressure variations such as the El Niño Southern Oscillation or the Northern Atlantic Oscillation (Bindoff et al., 2007). This is why longer-term tide gauge records or published analyses of sea level trends are preferable (Church & White, 2006; Church, et al., 2006).



Figure 33. Map of Singapore, showing locations of tide gauge stations and the Sungei Buloh Wetland Reserve.

Global mean sea level increased at an average rate of  $1.8 \pm 0.5$  mm per year between 1961 and 2003 (Bindoff et al., 2007). Since the mid-1990s, satellite altimetry has shown rates of sea level rise of about 3 mm per year (Bindoff et al., 2007). The rates of sea level change from the Singapore tide gauges, apart from Jurong, are consistent with these global rates. This suggests that Singapore has no significant local influences on relative sea level change apart from global eustatic trends. Hence, a vulnerability assessment for the mangroves of Singapore could use the globally projected rates of sea level change as an exposure factor, resulting in the vulnerability score below:

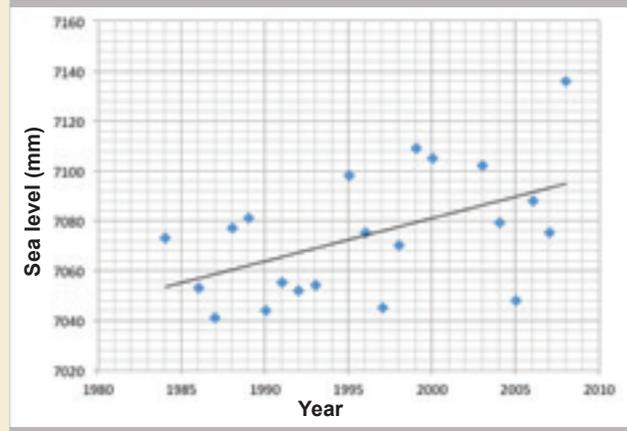


Figure 34. Annual mean sea level over time for Johor Bahru, 1994-2008. This is the tide gauge station with the longest data set that is closest to the Sungei Buloh mangrove area.

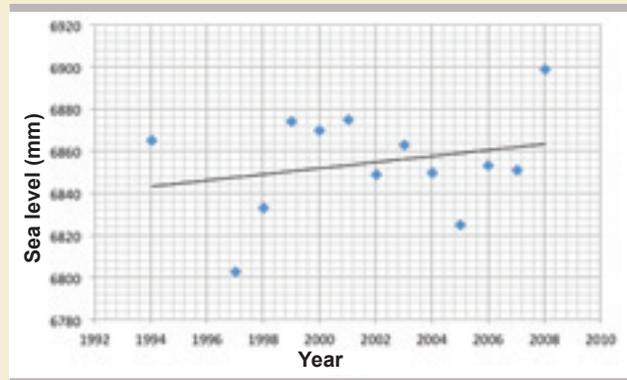


Figure 35. Annual mean sea level over time for Sembawang, 1994-2008.

Rank	1	2	3	4	5	S
<b>Exposure factors</b>						
Relative sea level rise (RSLR)	Site uplifting	Site slightly uplifting	Site stable	Site slowly subsiding	Site rapidly subsiding	<b>3</b>

### 3.5.2 Proxy methods

Although long-term tide gauges are a direct source of relative sea level data, many coastlines with mangroves either lack tide gauges or the record is too short to give a clear trend. If this is the case, the past relative sea level trends of a mangrove site can be reconstructed using stratigraphy or other types of proxy sea level reconstruction. In mangrove areas, stratigraphic cores and pollen analysis can be used to reconstruct relative sea level change for the last several hundred or few thousand years depending on the length of record found. Long-term net sedimentation rates can also be calculated from these records for use in subsection 3.6.

Details of fieldwork methods for coring and laboratory methods of pollen analysis and percent organic determination are given for mangrove environments in Ellison (2008). A link to the article is in the References.

#### How to analyze results

Studies of pollen in surface samples from a mangrove ecosystem have shown that there is a high *Rhizophora* pollen proportion in and immediately adjacent to the *Rhizophora* zone (Muller, 1959; Cohen & Spackman, 1977), and this can be used as a vertical indicator of former sea levels (Ellison, 2005, 2008). If stratigraphy reveals 60 percent or higher mangrove pollen presence, then deposits occurred in a mangrove forest (Muller 1959; Behling & Costa 2001). If this higher pollen presence is found below the current tidal range, then it indicates that the site is subsiding. If core sites are related to elevation datum (subsection 3.3), then rates of sea level change can be interpreted (Ellison, 2005).

Future sea level change of a coastal site can be worked out using the following formula:

$$\text{Future relative sea level (RSL)} = \text{global SLR projection} \pm \text{long-term RSL}$$

For example, if a coastline has long-term relative sea level rise (due to subsidence) of 4 mm per year, using the rates of global sea level rise projected by IPCC (2007b) of 1.5 to 9.7 mm per year, that coastline will experience relative sea level rise of 5.5 to 13.7 mm per year for the current century.

#### How to interpret vulnerability

As global sea levels rise, coastal areas that are subsiding will experience higher rates of relative sea level rise than areas that are stable. Such subsidence may be due to tectonic movement or deltaic compaction, isostatic adjustment and fluid extraction. This factor increases exposure.

Rank vulnerability on the scale at the bottom of the page. Record each score in the final column (S = score).

#### Strengths/weaknesses

Stratigraphic coring requires specialist skills and equipment and is best undertaken by involving a faculty member at a university department with suitable specialist skills. In the WWF pilots, work in Cameroon and Fiji was carried out by graduate students. Student thesis timescales need to be taken into consideration at the planning stages.

Core records can be inconclusive if the stratigraphy lacks depth, such as when the site is too rocky or has coarse sand or gravel or if a section is missing due to erosion or oxidation. This most likely happens if the sea level was previously higher and has fallen to present levels, causing rivers to become more active and exposing upper surfaces to oxidation. Sites that are subsiding, such as those described in the following case study, tend to give clearer results owing to continual submergence. One small benefit of these most vulnerable sites is that they are easier to identify through stratigraphy than are emerging sites, as the record is better preserved under water.

Rank	1	2	3	4	5	S
<b>Exposure factors</b>						
Relative sea level rise (RSLR)	Site uplifting	Site slightly uplifting	Site stable	Site slowly subsiding	Site rapidly subsiding	

## Case study

Coring sites in the Lomawai Reserve at Tikina Wai, Fiji (Figure 36) corresponded with mangrove forest assessment sites (Figure 6) established for the VA project along a transect from sea to land through the major mangrove area. Cores were taken at three locations on this transect across the center of the mangrove area, reducing the influence of local land-based edge effects; and elevations of mangrove species zones were surveyed (see case study at Figure 29). A Hiller corer (Figure 37) with a 1 m sidewall sample chamber length and 4 cm diameter was used, as elevation was critical and these sidewall sampling corers ensure no compaction (Ellison, 1989). A Russian peat corer (Figure 38) with a 50 cm sidewall sample chamber length and 5 cm diameter was also used to core through sandier stratigraphy that was not suitable for the Hiller corer. The corers were dismantled and washed following each meter or half meter cored to prevent any sample contamination, and

they were washed before the cylinder was opened to prevent contamination from upper layers.

The results diagram in Figure 39 shows that mangrove stratigraphy with high proportions of mangrove pollen occurred to at least 3 m depth below the surface. As mangroves occur only in a vertical microtidal range of 1 m at the surface (Table 14), this shows that the site must have been subsiding. The radiocarbon date of a sample at 2 m depth dated to about 1,000 years ago; about 80 percent dominance of mangrove pollen at that depth shows that mangroves were growing 2 meters below present at that time. This indicates slow relative sea level rise over the last millennium, consistent with tectonic subsidence.

Tests of the sediment to identify the proportion of organic content compared with inorganic mineral matter showed high input levels of inorganic sediment in association with

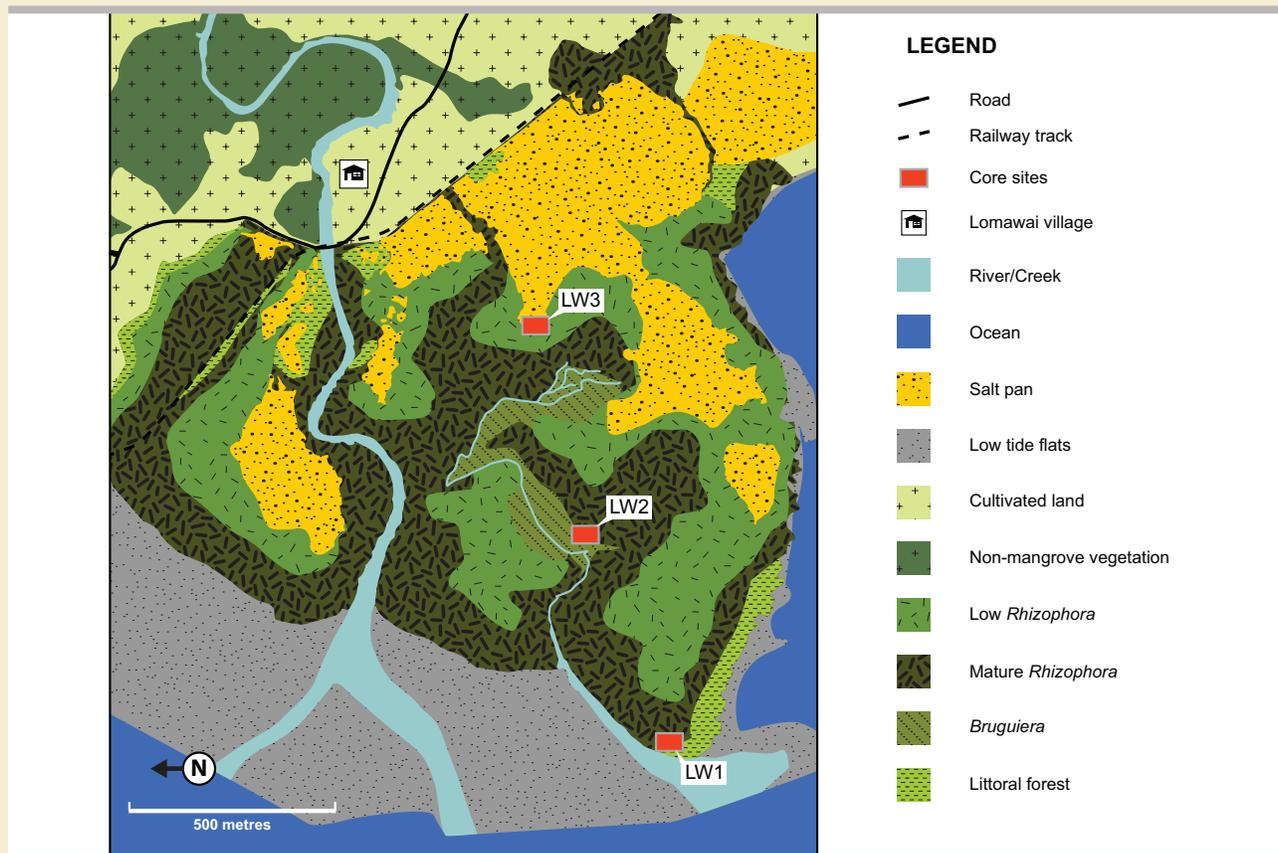


Figure 36. Map of coring sites on a shore-normal land to sea transect through the Lomawai Reserve, Fiji (from Ellison & Strickland, 2010b).

By Michael Helman



Photo Brigid Morrison

Figure 37. Hiller corer at Fiji core site LW3.

catchment sediment delivery at rates of at least 1.5 to 2.0 mm per year under the present mangroves. This mangrove area has been keeping up with relative sea level rise rates higher than current global rates in the last several hundred years, although with a slow landward migration of mangrove zones (shown by the change from *Bruguiera* to *Rhizophora* on the left in Figure 39). Hence, due to the area slowly subsiding, Tikina Wai mangroves are more vulnerable than stable sites to global increases in the rate of sea level rise – though this can be offset by continued catchment sediment delivery.

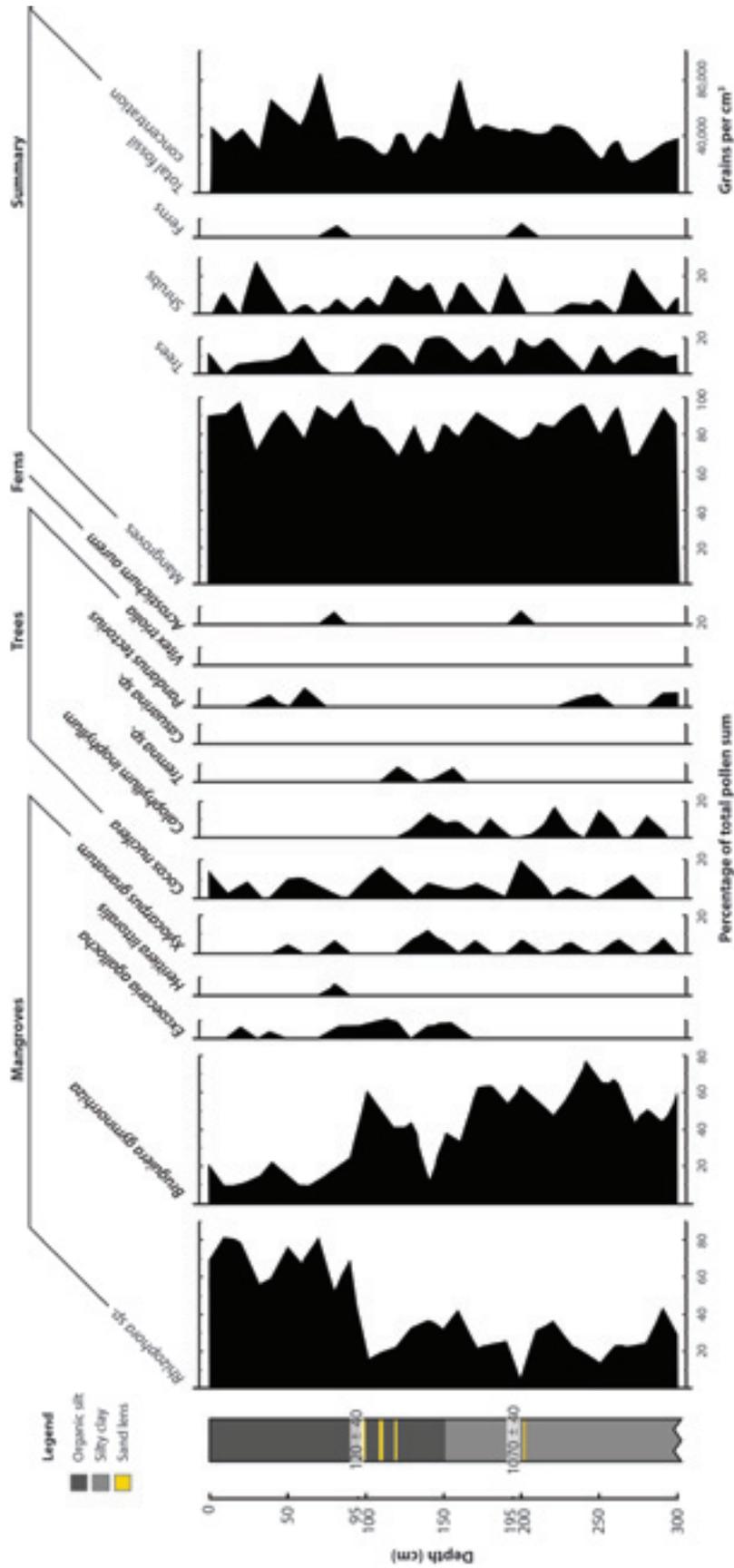
The vulnerability score is below:



Photo Brigid Morrison

Figure 38. Russian peat corer at Fiji core site LW3.

Rank	1	2	3	4	5	S
<b>Exposure factors</b>						
Relative sea level rise (RSLR)	Site uplifting	Site slightly uplifting	Site stable	Site slowly subsiding	Site rapidly subsiding	4



By Michael Helman

Figure 39. Stratigraphy and pollen diagram from core LW1, Lomawai, Fiji (adapted from Ellison & Strickland, 2010b).



Photo: Brigid Morrison

## 3.6 Sedimentation rates under mangroves

Approach	Expertise/ Technology needed	Time taken	Cost	Contribution to VA
Tables	High	Moderate	High	High
Stratigraphy	Rather high	Some	Rather high	Rather high
Stakes	Some	Some	Some	Moderate

### What is it?

This method involves measurement of the rate of accretion or erosion of sediment under a particular area of mangroves.

The sediment supply rate is an exposure factor, while the actual sedimentation rate under mangroves is a sensitivity factor.

### Why do it?

Sedimentation in mangroves allows the mangrove substrate to “keep up” with sea level rise and thus reduces the impacts of increased inundation stress. Sediment accretion allows the mangrove substrate to grow upward as a natural adaptation process in mangrove systems. If accretion is at the same rate as relative sea level rise, then tidal inundation frequencies are maintained and mangrove vulnerability to rising sea level is much reduced.

### How to collect data

Short-term rates of sedimentation can be measured using high-technology “sediment elevation tables” or low-technology sedimentation stakes, or long-term net sedimentation rates can be calculated from radiocarbon dates on stratigraphy (subsection 3.5.2).

### 3.6.1 High-technology: sediment elevations

The use of surface elevation tables and associated techniques can allow quantification of the different contributions to mangrove sediment accretion, such as organic detritus from the mangroves, mineral sediment from river discharge and soil volume change or compaction (Cahoon et al., 2002; McLeod & Salm, 2006; Cahoon et al., 2006; McKee et al., 2007;

Krauss et al., 2010) (Figure 40). For a climate change vulnerability assessment, the net vertical accretion resulting from these is the sensitivity factor. The WWF pilots did not test this high-technology approach, although such an approach would be valuable if the resources are available.

### 3.6.2 High-technology: radiocarbon dates from stratigraphy

Long-term net sedimentation rates can be calculated from radiocarbon dates on mangrove stratigraphy, using the data obtained in subsection 3.5.2. Such rates are calculated based on the average for the longer-term record (McKee et al., 2007) and do not indicate any variation during different time periods between dated samples.

On mangrove stratigraphy, use a section where pollen analysis identifies that it is mangrove strata, such as the 80 percent mangrove pollen consistent through the 3 m depth of the Lomawai seaward core in Figure 39. Table 17 shows the dating results from that core and others, with the dates reported by the radiocarbon laboratory as BP “before present” (where “present” = AD 1950). The calendar-calibrated result is shown in the 2-sigma calibration column; the 3rd and 4th columns are reported from the radiocarbon laboratory. In cases where there are two results, which occurs when there are two close crosses on the calibration curve, use both. Correct the years BP 2-sigma calibration result from 1950 to the date the core was collected. In the WWF pilot, this was 2007; so in Table 17, 57 years were added.

Then divide the upper and lower depth of the core sample (column 2, in mm) by the upper and lower error margins of the corrected date (column 5). This gives a net rate of vertical accretion above the

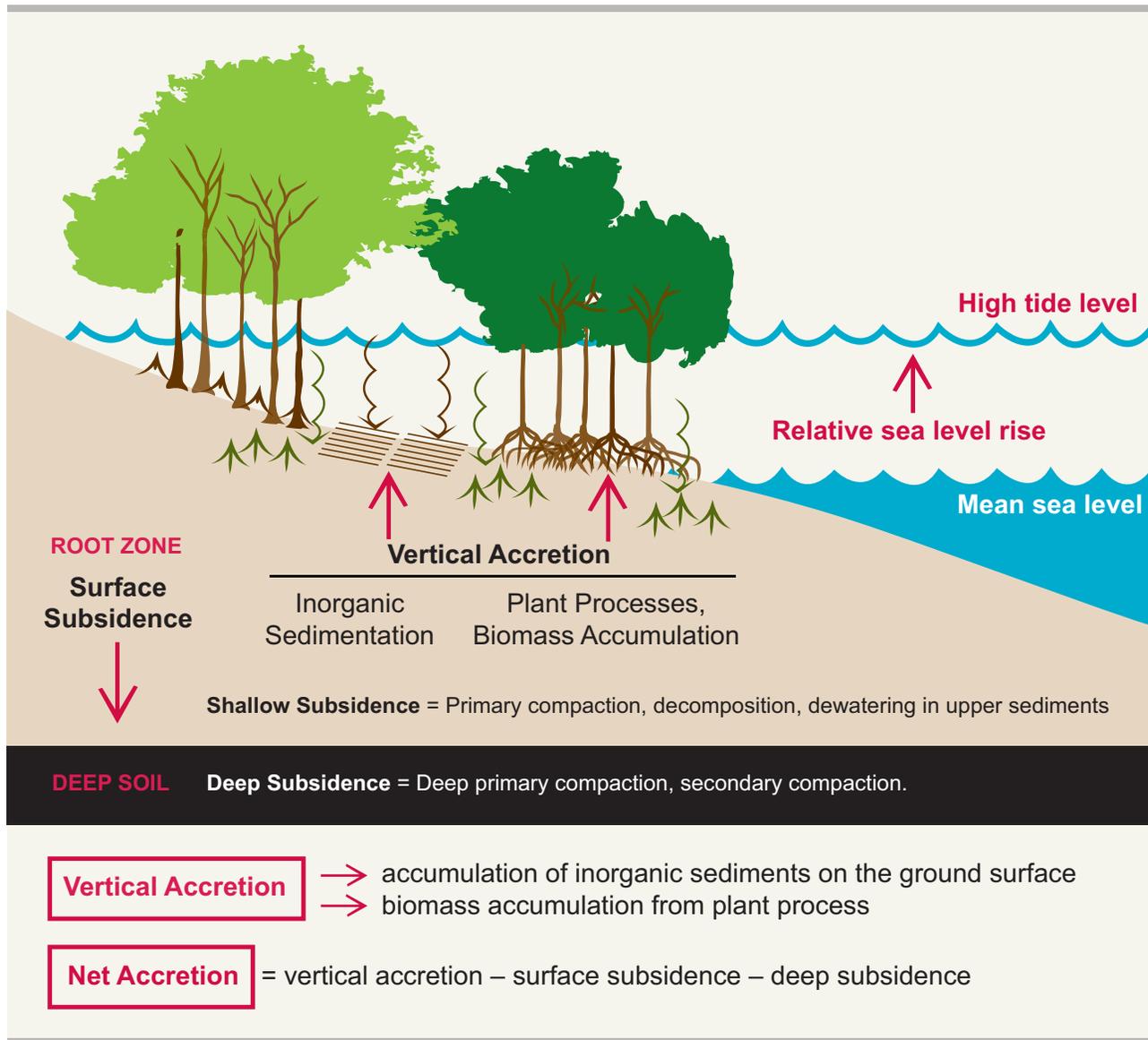


Figure 40. Model indicating the processes influencing vertical accretion in mangrove ecosystems (adapted from Cahoon et al., 1999).

calibrated radiocarbon date in mm per year, qualified by the error margin of the date and the depth.

Results are also shown in Table 17 from two other landward stratigraphic cores at Lomawai (Figure 36), to put the seaward core results into context. Net sedimentation rates are shown to be highest in the recent period at the seaward site, which may relate to recent disturbance in the catchment or storm activity, which is also shown in the sedimentation stakes case

study in the next subsection. Otherwise, sedimentation rates were found to be consistent at around 1 to 2 mm per year.

How to interpret vulnerability and strengths/weaknesses for this and other methods of estimating sedimentation rates are explained in subsection 3.6.4.

Core site	Depth mm	Conventional age (years BP)	2-sigma calibration	Corrected from 1950 (total years)	Sedimentation rate (mm per year)
LW1	930–980	120 ± 40	Cal AD 167–1780 (Cal BP 280–160) Cal AD 1790–1960 (Cal BP 160–0)	217–337 57–217	4.3–17.2
LW1	1930–1980	1070 ± 40	Cal AD 890–1030 (Cal BP 1060–920)	977–1117	1.7–2.0
LW2	930–960	510 ± 40	Cal AD 1330–1340 (Cal BP 620–610) Cal AD 1400–1450 (Cal BP 560–500)	667–677 557–617	1.6–1.7
LW3	630–710	430 ± 40	Cal AD 1420–1500 (Cal BP 530–440) Cal AD 1600–1610 (Cal BP 350–340)	497–587 397–407	1.1–1.8

**Table 17. Calculation of sedimentation rates from stratigraphic core dates. Example using three cores from Lomawai, Fiji (adapted from Ellison & Strickland, 2010b).**

### 3.6.3 Low-technology: sedimentation stakes

The sedimentation stakes approach (Gilman et al., 2007a) is more feasible for low-budget projects and is suitable for use with local community partners. It measures net vertical accretion, which results from factors such as organic detritus from the mangroves, mineral sediment from river discharge and soil volume change/compaction (Figure 40).

#### Equipment Required

- Narrow PVC pipe sections, 1.5 m long – 10 per permanent plot
- Small builder's level (see Figure 41)
- Hand-held stiff tape measure
- Personal safety gear
- Pencils and copies of data sheets (in Appendix)

#### How to collect data

- (a) By using the permanent plot sample design from the forest assessment (subsection 3.2), the fieldwork can be easily combined. At each permanent plot (subsection 3.2.2), go to one side where the mud is undisturbed and select a location that is unlikely to be stepped on.
- (b) Put into the mud a line of sedimentation stakes, 10 in a row, spaced 1 m apart. Push each stake into

the mangrove substrate so that only about 30 cm of the stake is sticking out of the sediment surface.

- (c) Measure each sedimentation stake, facing one direction, such as the seaward edge of the mangroves, and record the direction that was faced. Place a small level on top of the stake (Figure 41) and measure the height of the stake above the mud surface. This is better than measuring down the side of the stake as there may be water scour around the stake base later. Using the level ensures the measurement is horizontal with the top of the stake. Record these measurements on the data sheet.



Photo: Joanna Ellison

**Figure 41. Sedimentation stake measurement at Tikina Wai, Fiji.**

(d) Remeasure the stakes later using the same technique. Remeasurement is most effective if done the same month one year later and in subsequent years, to avoid seasonal changes that may give misleading results.

**How to analyze results**

At each observation point, on stake remeasurement, calculate the mean change as follows:

$$\text{Mean change (mm)} = \frac{\text{Total of (1st reading-2nd reading)}}{\text{Number of stakes}}$$

$$\text{Rate of change (mm per year)} = \frac{\text{Mean change} \times 365}{\text{Number of days between measurements}}$$

If the results are negative, this means the site is eroding. If the results are positive, this means the site is accreting.

During the productive season, such as summer, there will be greater productivity, while during the wet season there will be inorganic sedimentation at riverine sites. Sedimentation rate results are usually far higher than long-term net rates as calculated from stratigraphy (see subsection 3.6.2), mainly because they lack the compaction that comes with depth.

**3.6.4 How to interpret vulnerability**

This section is applicable to sedimentation rates derived from tables, stakes or stratigraphy.

Sediment supply rates result from mangrove geomorphic settings (Table 2), and this is an exposure factor. River-dominated mangroves generally have high sediment supply rates from river floods, while low island mangroves have low sediment supply rates because they lack rivers. Wave- and tide-dominated mangroves have higher sediment supply rates than low island settings. A sediment supply vulnerability score can thus be derived from the geomorphic setting of the area, such as:

Large river delta = High sediment supply, so low vulnerability

Medium catchment estuary = Medium sediment supply, so medium vulnerability

Low island setting = Low sediment supply, so high vulnerability

Low sedimentation rates under mangroves increase the vulnerability of mangrove systems to climate change impacts because sediment accretion allows mangrove substrates to “keep up” with sea level rise and so maintain tidal inundation frequencies. This is the most critical sensitivity factor of a mangrove vulnerability assessment and is best compared with the relative sea level change rate, as determined in subsection 3.5.

Rank vulnerability on the scale at the bottom of the page, either site by site or calculated as an average for the mangrove area. Record each score in the final column (S = score).

**Strengths/weaknesses**

Results from sedimentation stakes are a low-technology indication of vertical accretion as a result of the sedimentation and plant processes factors shown in Figure 40, but cannot account for the other subsurface factors depicted there. To do this, high-technology sediment elevation tables are required (see subsection 3.6.1). Results can be variable due to storm events; so appear changeable when compared with long-term net sedimentation rates as shown by radiocarbon dates.

These results do, however, indicate erosion or accretion; accretion is again preferable as it helps to reduce vulnerability to sea level rise.

The WWF pilots found that the regular remeasurement of sedimentation stakes is a great capacity-building activity for local communities. The activity is easy to understand and can be very engaging if the facilitator announces the previous measurement before a new reading is taken – particularly if results show accretion.

Rank	1	2	3	4	5	S
<b>Exposure factors</b>						
Sediment supply rate	High	Fairly high	Medium	Fairly low	Low	
<b>Sensitivity factors</b>						
Sedimentation rates in mangroves	Greater than RSLR	< 1 mm greater than RSLR	Equal to RSLR	< 1 mm less than RSLR	> 1 mm less than RSLR	

## Case study

The sedimentation stakes method was tested in Tikina Wai, Fiji (Figure 42). The results (Table 18) show, in most cases, that the stake measurements reduced over time, indicating accretion. Some isolated instances showed erosion, due to local scouring or crab activity.

Site 2 is located in the center of the Lomawai Reserve (Figure 42). It was remeasured during a regional training program in November 2010, and from this longer period of data than the others, an overall net sedimentation rate can be calculated.

Table 19 shows how to calculate a mean net sedimentation rate in mm per year:

- Subtract the second reading from the first at each stake to give the change over time.
- To get mm per day, divide by the total number of days between measurements; for example, in

Table 19, between 27 June 2007 and 10 November 2010 is  $1,231 (187+365+365+314)$ .

c) Multiply by 365 to get mm per year.

d) Average all 10 stakes at the site to get a site mean, as in the right-hand column of Table 18.

Calculating an average for all site stakes over a period that is from one time of the year (such as June/July) to one year later gives the most representative rate. The mean of the five sites in Table 18 that were remeasured is 14.9 mm per year. This shows high rates of sediment deposition during this period, which will allow this mangrove area to keep up with rising sea level as it has in the past (see subsection 3.5). Table 19 shows that high sedimentation occurred after July 2008, which is probably related to a river flood event and catchment erosion. Although positive sedimentation is a natural adaptation for mangroves to keep up with sea level

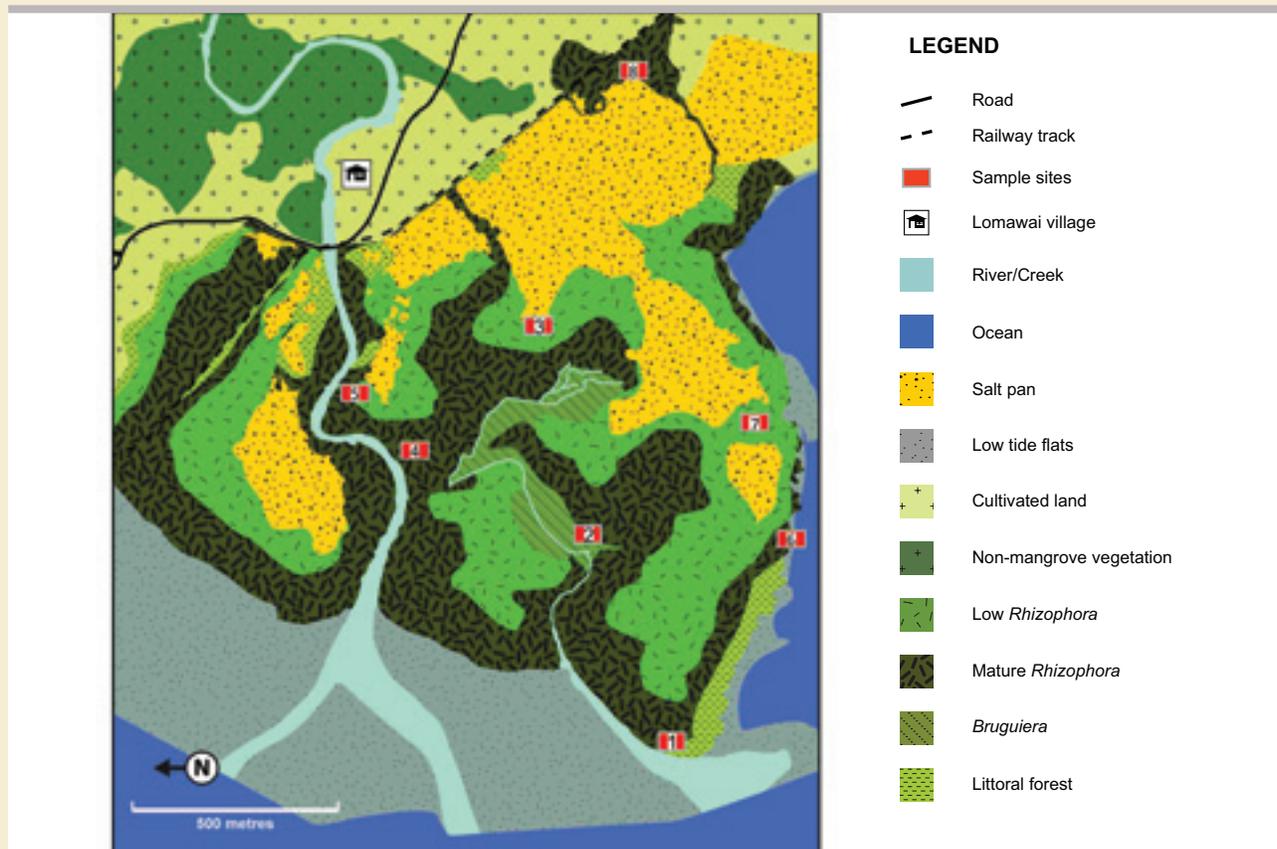


Figure 42. Sedimentation stake measurement sites at the Lomawai Reserve, Fiji.

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### 3.0 Conducting a Vulnerability Assessment

Site	Date	(Stake)										Rate mm/ year
		1	2	3	4	5	6	7	8	9	10	
1	27 June 07	230	182	180	153	132	199	170	181	186	190	24.0
	22 July 08	182	169	148	149	122	192	127	118	173	166	
2	27 June 07	314	258	284	258	264	253	205	264	324	321	5.78
	22 July 08	288	258	277	266	257	257	239	260	330	296	
	7 Nov 10	165	125	130	140	200	40	143	150	175	105	
4	27 June 07	170	167	144	102	119	127	153	146	140	112	42.5
	22 July 08	110	130	90	15	10	7	178	156	missing	89	
6	27 June 07	166	97	144	185	163	160	168	195	193	148	0.28
	22 July 08	100	159	148	144	191	158	178	197	187	154	
7	27 June 07	144	130	174	158	140	182	168	186	190	168	2.14
	22 July 08	132	164	179	177	183	137	125	148	168	204	
8	27 June 07	204	248	211	250	251	231	256	245	230	251	no data
	22 July 08											

**Table 18. Data collected from sedimentation stakes at mangrove monitoring sites, Tikina Wai, Fiji (mm) (from Fiu et al., 2010). The rate of change (mm per year) in the right-hand column is calculated as shown in Table 19.**

27 June 07	314	258	284	258	264	253	250	264	324	321
22 July 08	288	258	277	266	257	257	239	26	330	296
7 Nov 10	165	125	130	140	200	40	143	15	175	105
Change (mm)	149	133	154	118	64	213	107	114	149	216
mm per day	0.12	0.11	0.13	0.10	0.05	0.17	0.09	0.09	0.12	0.18
mm per year	44.2	39.4	45.7	35.0	19.0	63.2	31.7	33.8	44.2	64.1

**Mean for site = 42.0 mm per year**

**Table 19. Calculation of net sedimentation rate for site 2 in Table 18.**

rise, rapid sediment burial can smother mangrove roots and cause tree mortality (Ellison, 1998).

Hence, the following vulnerability score was obtained for Lomawai:

Rank	1	2	3	4	5	S
<b>Exposure factors</b>						
Sediment supply rate	High	Fairly high	Medium	Fairly low	Low	<b>3</b>
<b>Sensitivity factors</b>						
Sedimentation rates in mangroves	> 1 mm greater than RSLR	< 1 mm greater than RSLR	Equal to RSLR	< 1 mm less than RSLR	> 1 mm less than RSLR	<b>2</b>

## 3.7 Adjacent ecosystem resilience

Approach	Expertise/ Technology needed	Time taken	Cost	Contribution to VA
Coral reefs	Rather high	Rather high	Rather high	Moderate
Sea grass	Some	Some	Some	Moderate

### What is it?

Similar to subsection 3.2, forest assessment of mangroves, this method involves a baseline assessment of the status and condition of adjacent systems that are connected to the mangrove system through catchment linkages.

Resilience in ecosystems adjacent to mangroves is a sensitivity factor.

### Why do it?

Ecosystems adjacent to mangroves, such as coral reefs and sea grass beds, are connected biophysically through food chains, sediment budgets and other reciprocal services. Assessment of adjacent ecosystem health therefore contributes to a mangrove vulnerability assessment in that, if such ecosystems are in poor condition, they will increase the mangrove area's vulnerability to change and perturbation.

The following coral reef and sea grass monitoring methods adhere to international standard protocols, creating a baseline survey against which future change can be measured and allowing comparison of results with sites elsewhere that use the same methods.

### How to collect data

Protocols for baseline assessment and monitoring of coral reefs and sea grass are available at the following websites:

IUCN Climate Change and Coral Reefs Marine Working Group  
[www.iucn.org/cccr](http://www.iucn.org/cccr)  
[www.cordioea.org/resources](http://www.cordioea.org/resources)

Coastal Oceans Research and Development in the Indian Ocean  
<http://www.cordioea.org/>

Seagrass Watch  
<http://www.seagrasswatch.org/manuals.html>

The following methods are based on these protocols.

### 3.7.1 Coral reefs

These methods were developed by the IUCN working group on Climate Change and Coral Reefs (Obura & Grimsditch, 2009) to assess the resilience of coral reefs to climate change (high seawater temperatures). For full details, see the websites above.

Several components of a reef ecosystem can be measured using these methods at varying levels of detail, as follows:

1. Benthic cover provides the main overall indicator of reef state, particularly the balance between corals and algae, and is measured by standard monitoring programs — in this case, using digital photographs analyzed afterward on the computer.
2. Coral community structure provides an overview of the coral community and the relative abundance of genera that are susceptible or resistant to coral bleaching. It is estimated during field visits along a five-point scale from rare to dominant.
3. Coral population structure/size class distributions give the most accurate information on the demography and sizes of coral colonies and can show indications of past impacts by the presence or absence of large colonies. The method includes sampling of recruitment, i.e., of new corals settled from larvae, showing the recovery potential of the coral community.
4. Coral condition gives an indication of the current health of the coral community and includes observations on bleaching, disease and mortality and the presence of predators and threats, such as crown-of-thorns sea stars.
5. Fish populations exert control on the benthic community, particularly through herbivory, which limits the proliferation of algae that can outcompete corals. The number of fish in different functional groups (i.e., that feed in different ways

on algae and have different impacts on its growth and spreading) is measured.

6. Resilience indicators are factors that affect the resistance of corals to bleaching and the resilience or recovery potential of the reef community. A broad range of indicators in different classes is measured, some quantitatively and some by eye estimates.

This methodology has already been applied in 25 different areas globally (Obura, 2010), establishing a standardized method for assessing coral reef vulnerability to climate change. It is summarized further in Table 20.

A semi-quantitative five-point scale is used for estimating most of the indicators (Obura & Grimsditch, 2009; Obura, 2010), except for those (like temperature

and visibility) that could easily be measured or estimated quantitatively. Classification of the five-point scale is done using local and regional knowledge.

**How to interpret vulnerability**

Where adjacent coral reefs are in poor condition, mangroves have reduced sediment supply from offshore productivity, reduced protection from wave action and reduced quality of adjacent habitats used by mangrove species such as fish. Hence, reduced quality of adjacent coral reefs increases the sensitivity of mangroves to climate change impacts.

Rank vulnerability on the scale at the top of the next page, either site by site or calculated as an average for the area. The semi-quantitative five-point scale of Obura & Grimsditch (2009) and the resilience scale of

Component	Method/approach	Equipment required
1 Benthic cover	Compatible with standard long-term monitoring approaches. Uses point transects.	Genus guide for corals
2 Coral community structure (genera)	Visual estimate — relative abundance of genera at the study site, in 5 classes: 5 = dominant 4 = abundant 3 = common 2 = uncommon 1 = rare	Data sheets — benthic, fish, invertebrates
3 Coral size class distributions (selected genera)*	Belt transects (25 x 1 m, four replicates) with sub-sampling using quadrats for colonies > 10 cm. 15–20 selected genera, in doubling size classes (0–2.5, 3–5, 6–10, 11–20 cm, etc.)	1 m ruler/stick marked at 10, 20, 40 and 80 cm to help guide size estimates (3/4" PVC tube ideal for this)
4 Coral condition	Incidence of coral bleaching, disease, other conditions and mortality in the size distribution belt transects and in the general study site.	Benthic data sheet, Coral Watch coral health chart
5 Fish community structure — herbivores	Long-swim and belt transects (50 x 5 m, three replicates) recording incidence of large indicator fish and main functional groups, focusing on herbivore functional groups	50 m line transect, data sheet with ID sheet of main groups
6 Resistance and resilience indicators	Visual estimation (e.g., slope) or 5-point scale of resistance and resilience indicators across multiple factors: • benthic cover • physical site parameters • substrate and reef morphology • cooling and flushing • shading and screening • extreme conditions and acclimatization, coral condition • coral population structure and coral associates • fish functional groups (herbivory) • connectivity and anthropogenic conditions	

**Table 20. Summary of the resilience assessment for coral reefs (Obura & Grimsditch, 2009; Obura, 2010).**

Rank	1	2	3	4	5	S
<b>Sensitivity factors</b>						
Adjacent coral reef resilience	Very high	High	Moderate	Low	Very low	

Obura's (2010) can be used, but reverse the resilience scale score so that it refers to vulnerability. Record the score in the final column (S = score).

### Strengths/weaknesses

If coral reefs are closely adjacent to the mangrove site, such as a fringing or barrier reef on a small island or low coastal site, they are important to the mangrove vulnerability assessment.

A coral reef resilience survey has the capacity to expand into a large project, particularly if keen divers and coral scientists become involved. Involvement with a long-term coral reef monitoring project would be helpful for guidance and data sharing.

## 3.7.2 Sea grass

Seagrass Watch's standard methods for baseline assessment and monitoring of sea grass community structure and condition are available at <http://www.seagrasswatch.org/manuals.html>

### How to collect data

Follow the guidelines in the Seagrass Watch manuals (McKenzie & Campbell, 2002; McKenzie et al., 2003). These are written for citizens, not specialists, and this is a good exercise in which to involve the local community.

Record characteristics of sea grass habitat adjacent to mangrove areas, including

- geographic location
- visual estimates of above-ground biomass percentage cover (4 replicates of a 0.25 m<sup>2</sup> quadrat)
- species composition
- percent algae cover
- sediment type
- water depth

### Equipment Required

- 4 x 0.25 m<sup>2</sup> quadrats
- Sea grass ID guide
- Data sheets (3 per transect x 3 transects per site)
- 50 m measuring tape
- 30 cm ruler
- Compass

### How to interpret vulnerability

Where sea grass communities adjacent to mangroves are in poor condition, mangroves will have reduced sediment supply from calcareous sea grass productivity, reduced protection from wave action and reduced quality of adjacent habitats used by mangrove species, such as fish. Hence, reduced resilience of adjacent sea grass increases the sensitivity of mangroves to climate change impacts.

Using the guidance in the Seagrass Watch manuals rank vulnerability on the following scale, either site by site or calculated as an average for the area. Record the score in the final column (S = score).

Rank	1	2	3	4	5	S
<b>Sensitivity factors</b>						
Adjacent sea grass resilience	Very high	High	Moderate	Low	Very low	

### Case study

At Tikina Wai in Fiji, sea grass surveys and monitoring have been conducted through WWF's ongoing community-based Seagrass Watch program (Fiu et al., 2010). Survey methods for assessing health and extent of sea grass along the coastline were adapted from the Seagrass Watch survey protocol. A comprehensive survey was carried out, based on the probability of significant sea grass communities, accessibility to coastline and the easy-to-use survey guidelines for community engagement. These sea grass sites along the shoreline and adjacent barrier reef flats included representative examples of marine habitats of interest and mangrove areas. The surveys (Figures 43 and 44, Table 21) were carried out in November 2007 and July 2008 and primarily focused on providing detailed information (distribution and abundance) on high-priority intertidal and shallow subtidal sea grass ecosystems along the Tikina Wai coastline.

Table 21 shows sea grass cover and fauna distributions across sea grass areas of the mangrove-dotted coastline and also found at the shallow reef flats of the adjacent barrier reef slope. Four sea grass species found growing along the shores were identified as *Syringodium isoetifolium*, *Halophila ovalis*, *Halodule uninervis* and *Halodule pinifolia*. The predominant species along offshore transects were *Halodule pinifolia* and *Syringodium isoetifolium*, which are also common along the mangrove shoreline.

Moving away from the mangroves toward the reef flat edge, a slope of silt and sand was located with a mixed assemblage of *Halimeda*, *Padina*, *Hydroclathrus* and low-density sea grass as compared to the two other



Photo: Monifa Fiu

Figure 43. Sea grass monitoring at Tikina Wai, Fiji.

mangrove areas. The Lomawai site is close to the mouth of a main river and so is more influenced by freshwater influx and intermittent flooding with heavy rains than the seaward reef slope, affecting sea grass growth.

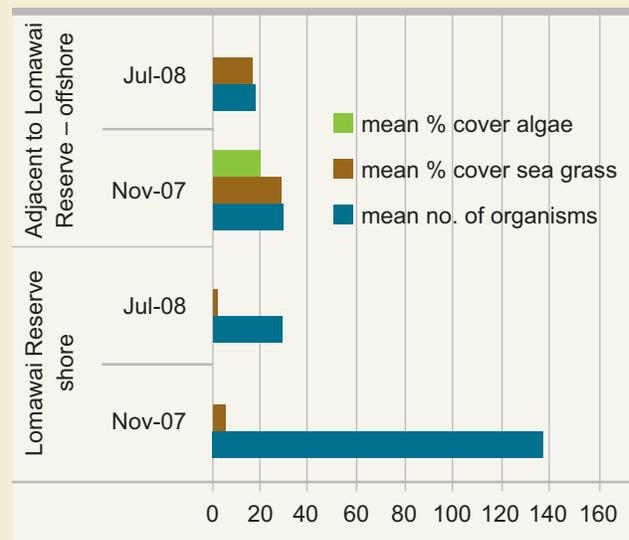


Figure 44. Lomawai Seagrass Watch results 2007–2008.

		Mean no. of organisms	Mean % cover sea grass	Mean % cover algae
Lotonaluya Reserve shore	Nov. 07	18.8	23.1	16.6
	Jul. 08	28.1	9	5.2
Adjacent to Lotonaluya Reserve – offshore	Nov. 07	0.3	4	6
	Jul. 08	1	0.2	19.5
Bole Reserve shore	Nov. 07	4.3	23.3	34.7
	Jul. 08	8.8	2.1	10.6
Adjacent to Bole Reserve – offshore	Nov. 07	1.3	42.2	20.5
	Jul. 08	1.3	23.5	4
Lomawai Reserve shore	Nov. 07	137	4.4	0.5
	Jul. 08	29.3	1.5	0.4
Adjacent to Lomawai Reserve – offshore	Nov. 07	30.3	28.6	20.3
	Jul. 08	17.4	16.5	1.5

Table 21. Tikina Wai sea grass cover and fauna distribution across sea grass sites adjacent to mangroves.

Generally, sea grass transects along the offshore reef flats recorded higher invertebrate counts and thicker sea grass growth. This coastal region is an important fishing ground for the coastal community, including the villages of Tikina Wai. The most intensely gleaned area is the offshore reef flats where the sea grass grows.

The November 2007 surveys were conducted during the cyclone season, and perceived impacts were attributed to the physical impact of strong wind and wave action plus associated heavy rain that created turbidity in the water. It was noted that, where sea grass grows, there were no evident signs of erosion or disturbance on the sediment-deposited shoreline.

The July 2008 surveys coincided with the sugarcane harvesting season, and the prevalent burning of cane fields up on the hills during this period evidently affected the sea grass habitat. Blown ash from the burning heavily coated the sea grass canopy,

causing extensive browning of the leaves of mainly *Syringodium isoetifolium* and *Halodule pinifolia*. Results indicated a decline in the extent of sea grass growth and associated fauna, with the physical environment affected by the increased stormy and windy conditions affecting this region. However, the most immediate threat to the integrity of the sea grass and mangrove habitat is tourism development, which has been planned for the nearby lagoon of Wai.

Table 21 shows declines in sea grass cover at all sites during the monitoring period and loss of diversity at some. Offshore sites fare better than near-shore sites, which allows some resilience if pressures such as human gleaning and ash fallout are reduced. The vulnerability score below is therefore categorized as moderate, although it would be low without the offshore sites.

Hence, the following vulnerability score was obtained for Lomawai:

Rank	1	2	3	4	5	S
<b>Sensitivity factors</b>						
Adjacent sea grass resilience	Very high	High	Moderate	Low	Very low	3

## 3.8 Climate (rainfall) modeling

Approach	Expertise/ Technology needed	Time taken	Cost	Contribution to VA
Available projections	Moderate	Some	Low <sup>3</sup>	Some

### What is it?

This method involves a review of detailed projections for climate change effects on rainfall for the mangrove area and for the catchment areas of any rivers delivering surface water to the mangrove area, using global models and/or downscaled regional models where available (these give a higher-resolution output than global models).

Climate change, particularly with respect to rainfall and humidity changes, is an exposure factor.

### Why do it?

The predicted effects of climate change factors on mangrove ecosystems listed in Table 1 show that mangroves are not expected to be vulnerable to increased temperatures, increased CO<sub>2</sub> concentrations, or wetter conditions. One exception is where extreme events bring prolonged flooding, which causes mangrove mortality (Breen & Hill, 1969; Jimenez & Lugo, 1985; Steinke & Ward, 1989; Forbes & Cyrus, 1992; Choy & Booth, 1994; Erfteimeijer & Hamerlynck, 2005).

Reduced rainfall and reduced humidity, however, have a negative effect on mangrove productivity (Table 1), but given that productive mangroves exist in some of the driest areas on Earth (Ellison & Simmonds, 2003), these occurrences are unlikely to cause their total loss. As the precipitation projections in climate change models improve, such modeling will become more useful for a mangrove vulnerability assessment.

### How to collect data

As discussed in subsection 3.1, modeled data of future climate change scenarios may be available for the vulnerability assessment area through partners, stakeholders or other projects. Key stakeholders to approach are meteorological agencies, focal government departments responsible for climate change or regional climate change institutions.

In many cases, such downscaled modeling outputs may not be available from secondary sources, in which case they can be commissioned from specialist institutions with modeling expertise, such as universities or national meteorological agencies. However, practitioners will want to consider whether the resulting expense is the best use of available resources in view of the uncertainty and unpredictability currently involved in generating future rainfall projections. The value of downscaled projections will also depend on the number of meteorological stations in the vicinity of the target area and the temporal span of the data, which poses a limitation particularly in sub-Saharan Africa.

### How to analyze results

Use model results to analyze different rainfall parameters relative to recent conditions such as:

- mean monthly rainfall
- mean daily rainfall
- monthly 90th percentile daily rainfall
- monthly days exceeding 90th percentile
- monthly mean dry spell duration

A significant increase in drier conditions may cause reduced productivity and diversity in mangroves or at riverine sites and in the usually more diverse landward margins of mangroves. Species such as *Avicennia bicolor*, *Sonneratia caseolaris*, *S. lanceolata*, *Rhizophora racemosa*, *Pelliciera sp.* (Duke et al., 1998) and *Nypa fruticans* are upstream species of freshwater-dominated riverine systems that are particularly vulnerable to increases in salinity caused by drier conditions.

<sup>3</sup> Refers just to use of the data, not the actual setup and maintenance of a climate model – which is high-technology, expensive and requires lengthy data sets.

### How to interpret vulnerability

Although higher temperatures are not a vulnerability factor for mangroves, adjacent coral reef systems are vulnerable to temperature increases (see subsection 3.7).

Changes in rainfall patterns and downscaled rainfall projections may show rainfall trends, as well as demonstrate changes in seasonality of rainfall (which might affect phenology). Changes in frequency of dry spells can affect mangroves separately from the longer-term trends.

More severe or more frequent freshwater flooding events are excluded from the vulnerability assessment even though they cause mortality as mentioned earlier. This is because site-specific storm impacts are impossible to predict, and overall sea level inundation vulnerability is covered in subsection 3.5.

Drier conditions may increase the vulnerability of mangroves, such as through reduced diversity, photosynthesis and productivity, as well as ground-

level subsidence (Table 1). However, as demonstrated in the case study below, rainfall projections currently tend to be highly uncertain and hence difficult to quantify. This will improve as rainfall modeling becomes more sophisticated.

Rank vulnerability on the scale below. Record the score in the final column (S = score).

### Strengths/weaknesses

Data on changes in ground level and forest diversity and condition are collected in the forest assessment, elevation and sedimentation components of the vulnerability assessment already described. From these baseline surveys, such changes can be monitored in the future and the results interpreted relative to rainfall changes. Rainfall projections within downscaled climate modeling may eventually improve in their level of certainty, which would make them more useful for mangrove vulnerability assessment.

Rank	1	2	3	4	5	S
<b>Exposure factors</b>						
Precipitation change	Becomes wetter	Rainfall unchanged	Somewhat drier	Moderately drier	Significantly drier	

### Case study

Following traditional approaches in climate change vulnerability assessment, the WWF project initially investigated climate models for the pilot sites and found very uncertain results for the exposure factor of precipitation change (Table 22), in that it was predicted to either get wetter or drier.

In Fiji, downscaled modeling was undertaken to try to reduce this uncertainty. The results were inconclusive, with 7 of 12 models showing a future (2080–99) with higher annual rainfall than at present (1980–99). These results implied that it would be wise for environmental planners, when reviewing adaptation options, to consider both negative and positive rainfall projections for the 21st century. Hence, the modeling was of little help to the overall vulnerability assessment.

Regions	2010-2039	2040-2069	2070-2099
Mediterranean	-35.6 to +55.1	-52.6 to +38.3	-61.0 to +6.2
Caribbean	-14.2 to +13.7	-36.3 to +34.2	-49.3 to +28.9
Indian Ocean	-5.4 to +6.0	-6.9 to +12.4	-9.8 to +14.7
Northern Pacific	-6.3 to +9.1	-19.2 to +21.3	-2.7 to +25.8
Southern Pacific	-3.9 to +3.4	-8.23 to +6.7	-14.0 to +14.6

**Table 22. Projected change in precipitation over small islands, by region (percentage). The ranges are derived from seven atmosphere-ocean general circulation models (GCMs) run under the key SRES emissions scenarios (from IPCC, 2007c).**

## 3.9 Compilation of local community knowledge

Approach	Expertise/ Technology needed	Time taken	Cost	Contribution to VA
Workshops and questionnaires	Some	Some	Moderate	High

### What is it?

This component of the VA is a survey of community focus groups that involves engaging with them through a participatory learning and action process to understand environmental and climate change issues (Fiu et al., 2010). Local community surveys clarify the effectiveness of mangrove management capacity, stakeholder involvement and mangrove protection legislation.

Community management capacity and stakeholder involvement are both adaptive capacity factors. Mangrove protection legislation is a sensitivity factor, as its absence has an impact on mangroves. However, creating or strengthening such legislation improves adaptive capacity.

### Why do it?

Local community knowledge provides primary information for the VA, allowing for interpretation of GIS and forest assessment data with information on past trends in mangrove abundance and species composition; threats to mangroves, both natural and human; as well as the ways in which the mangroves are presently being used by people.

Interviews with local people also contribute information on the awareness of mangrove values and management regimes. These interviews may include collecting some basic socioeconomic information. Information from people living in or adjacent to the mangrove area complements results from other components of the VA, such as identification of past change through GIS analysis, erosion or accretion of the seaward edge, mortality of a certain mangrove species or changes in inundation regimes. Such information also makes it possible to identify needs for management and capacity building.

Local communities also have considerable experience of past climate variability and observations of current climate change, which can be documented and included in the VA.

### How to collect data

Use standard participatory rural appraisal (PRA) methods with a focus on the following factors:

- specific issues and features of the local setting and climate variability
- development of a seasonal calendar of observations, particularly relating to localized mangrove interactions with adjacent ecosystems
- changes over time of the mangrove area as far back as community memory allows.

Focus groups involving community members and resource users can be held in each village, and interviews can be conducted with key informants, such as elderly people who have lived in the area for the longest period of time and who are known for their knowledge and experience (Rubens et al., 2011). Discussions can utilize a predesigned list of questions, with follow-up questions as needed. Such social-science research must be carried out in accordance with the proper ethical standards.

Observations of climate variability can be documented using the WWF Climate Witness Toolkit,<sup>4</sup> which was created to document local experiences of climate change impacts and to devise appropriate adaptation measures that communities can implement themselves. Such participatory tools use timelines, community mapping and seasonal calendars for identifying observed changes in climate.

These approaches can identify and prioritize problems relating to potential extreme events and climate vulnerabilities and, using this information, compile community perspectives on adaptation measures that are most suitable for implementation. An illustration of how this process was carried out in Fiji appears in Figure 45, demonstrating how the VA process can lead a community toward adaptation planning.

<sup>4</sup> [http://wwf.panda.org/about\\_our\\_earth/all\\_publications/?162722/Climate-Witness-Community-Toolkit](http://wwf.panda.org/about_our_earth/all_publications/?162722/Climate-Witness-Community-Toolkit)

A socioeconomic component can be included in these community surveys and participatory exercises to inform the process of developing and implementing adaptation strategies. This component may investigate issues of control and access to land and resources, resource ownership and management and/or community dependency on particular resources.

In cases where community reliance on mangrove resources is high, indirect effects may cause a double exposure to climate change whereby reduced community resilience increases pressure on mangrove resources. Those who wish to explore this issue for a given area in greater detail are advised to refer to established approaches such as:

CARE's Climate Vulnerability and Capacity Analysis (CVCA) Handbook  
[http://www.careclimatechange.org/tk/integration/en/quick\\_links/tools/climate\\_vulnerability.html](http://www.careclimatechange.org/tk/integration/en/quick_links/tools/climate_vulnerability.html)

IUCN's CRiSTAL: Community-based Risk Screening Tool – Adaptation and Livelihoods  
<http://www.iisd.org/cristaltool/>



**Figure 45. Schematics of the community engagement process used in Fiji (Fiu et al., 2010).**

The Red Cross/Red Crescent's Community Risk Assessment approach  
<http://www.climatecentre.org/site/publications/121>

### How to analyze results

Inter-relate results from the community surveys with other sections of the vulnerability assessment to improve the overall interpretation of the nature of change. GIS evidence of long-term spatial change in the mangroves may be supported and explained by oral history. Forest assessment evidence of poor mangrove health or overexploitation can be clarified by focus groups and interviews and developed into adaptation approaches to improve mangrove monitoring and management. Sedimentation stake evidence of erosion or accretion can be supported by community observations about changes to nearby waterways.

### How to interpret vulnerability

Mangrove areas that have

- poor local management systems,
- weak protection legislation,
- limited stakeholder involvement in management, and
- vulnerable local communities that are likely to increase pressure on mangroves if livelihoods fail or adaptation options are limited

are more vulnerable to climate change.

Mangrove areas that have

- good local management systems,
- effective protection legislation,
- strong stakeholder involvement in management, and
- high stakeholder capacity for adaptation in ways that are unlikely to place additional pressure on mangroves

are less vulnerable to climate change.

Consider in these contexts the vulnerability of the mangrove area, using information from surveys of community knowledge, information on stakeholder involvement in management of the mangrove area and knowledge of the relevant legislation and its

Rank	1	2	3	4	5	S
<b>Sensitivity factors</b>						
Mangrove protection legislation	Good	Fairly good	Moderate	Poor	None	
<b>Adaptive capacity factors</b>						
Community management capacity	Good	Fairly good	Moderate	Poor	None	
Stakeholder involvement	Good	Fairly good	Moderate	Poor	None	

enforcement. This score will be judgemental and subject to site-specific circumstances.

Rank vulnerability on the scale above, either site by site or calculated as an average for the mangrove area. Record the score in the final column (S = score).

Mangrove protection legislation was identified as a sensitivity factor through the WWF pilots, since its relative strength or weakness affects mangrove condition and extent. However, improved, well-implemented legislation could increase adaptive capacity in the future.

**Strengths/weaknesses**

Coastal wetlands like mangroves are usually best managed by the local communities who have long been involved with them, and integration of local

management structures with the VA and adaptation process is necessary for its effectiveness. Participatory involvement of local communities and other stakeholders (see Section 2.4) will lead to greater success with these activities.

Social surveys are sometimes quasi-quantitative, and there may be barriers to communication or lack of support if the objectives of the VA and adaptation process are not fully understood.

If there is a contradiction – for example, between information on mangrove change from GIS analysis and information from oral history – then consider the error margins of each technique of data gathering. Perhaps the survey sample size was too small, or verbal reference to a particular area was not understood, in which case further surveys might be needed.

**Case study: Tikina Wai, Fiji**

Through a series of facilitated meetings in the various villages of the district, the local community systematically identified problems and their presumed causes as they affect the climate change vulnerability of their village and district (Table 23). Identification of these problems allowed the formulation of potential solutions that would guide community planning for adaptation.

Some of these consultation results were integrated with the more scientific components of the vulnerability assessment. For example, the community mangrove monitors became responsible for repeat

surveys of mangrove conditions (subsection 3.2.1) and sea grass resilience (subsection 3.7.2). The partnership developed with a local dive shop allowed for continued monitoring of coral reef resilience (subsection 3.7.1). Understanding the importance of sediment supply to the mangroves came from community involvement in the sedimentation stake deployment and remeasurement (subsection 3.6).

Such a process demonstrates how results can be analyzed by the community, and how adaptation options can then be prioritized. This process is facilitated by the guidance given below in Sections 4 and 5.

Overall, the Tikina Wai community surveys scored:

Rank	1	2	3	4	5	S
<b>Sensitivity factors</b>						
Mangrove protection legislation	Good	Fairly good	Moderate	Poor	None	<b>3</b>
<b>Adaptive capacity factors</b>						
Community management capacity	Good	Fairly good	Moderate	Poor	None	<b>1</b>
Stakeholder involvement	Good	Fairly good	Moderate	Poor	None	<b>1</b>

	Problem listing	Root cause analysis	Potential solution
Land	Freshwater shortage in dry season	Drought affects agricultural productivity and seasonality of traditional agricultural calendar  Shift in the planting of traditional crops and increasing dependence on purchased food (with limited income)	Increase water storage capacity and improve delivery of water in district  Increase understanding of alternative, more climate-smart crops
	Extreme rainfall events	Roads become impassable; breeding of mosquitoes and rise in waterborne diseases (dengue, diarrhea and skin diseases)	Increase school attendance flexibility  Improve roads  Develop better local income-earning opportunities  Improve community health education
	Sediment deposition in the intertidal areas  Increasing shallowness of rivers and loss of wetlands near waterways  Deeper areas in the tidal zone becoming shallow	Logged pine forest areas associated with periods of heavy rain experiences landslides and soil erosion  Absent buffer zones between pine forests and the river exacerbate siltation within the river system	Improve catchment management, such as logging in the dry season and use of riparian buffers  Increase understanding that sediment supply to the mangrove area is important for mangrove resilience to sea level rise
Tidal	Coastal flooding and erosion	Encroachment of the high tide mark inland, as compared to the past	Improve survey points in the village to allow accurate comparison of land levels with MSL levels  Raise bases of houses
		Mangroves encroaching into previously exposed salt pans mean loss of cultural heritage (the art of traditional salt making for which the district is renowned)	Gain funding for and build a more secure salt making facility on the highest section of the salt pan close to the village, also to facilitate tourism
	Excessive removal or cutting of mangroves from shoreline	Need for wood; Inadequate surveillance and community education	Appoint mangrove monitors for surveillance and reporting to resource management committee and require those who cut mangroves to replant them  Improve the traditional practice of bark harvesting so it does not damage tree health  Rehabilitate and replant mangroves
Coral reef	Coral bleaching events observed	Correlation with ENSO events such as in 2000	Develop partnership with a local dive shop for sea surface temperature monitoring on the barrier reef
	Increased crown-of-thorns incidence during drought years	Unknown	Increase observation and communication among lagoon users to allow monitoring, reporting to resource management committee
	Fish spawning seasonality uncertain (compared to historical timelines)	Changed climate and coastal conditions	Banning of commercial fishing in the marine protected areas  Improve communication among fishers to pool community knowledge on fish spawning patterns

Table 23. Community consultation results from Tikina Wai, Fiji and adaptation solutions.

### 3.10 Overview of resource requirements for the vulnerability assessment

Section 3 has described eight components of data gathering for a mangrove vulnerability assessment, following an initial review of existing information. Table 24 summarizes these components as rated in terms of the scale of expertise and technology required, time needed to do the work, cost and relative contribution to the VA synthesis, as will be discussed in Section 4. These ratings come from the summaries at the beginning of each subsection in Section 3. The cost factor is dependent on the size of the mangrove area and the logistics of fieldwork there.

The final column on the relative contribution of each component to the overall vulnerability assessment allows prioritization by those planning to go ahead with a VA. **Those components most critical to a VA are forest assessment by permanent plots and analysis of recent spatial change, relative sea level trends and sedimentation rates.**

Component	Approach	Expertise/Technology needed	Time taken	Cost	Contribution to VA
Initial review of existing information	Desktop	2	2	1	4
Forest assessment of mangroves	Rapid	2	3	2	4
	Plots	3	4	3–4	5
	Litter	3	5	3	2
Recent spatial changes	GIS	5	3	3	5
Ground surface elevations	dGPS	5	2	5	4
	Water level	2	2	2	4
Relative sea level trends	Tide gauge data <sup>5</sup>	3	2	1	5
	Stratigraphy/ pollen analysis	4	4	4	3–5 <sup>6</sup>
Sedimentation rates under mangroves	Tables	5	3	5	5
	Stratigraphy	4	2	4	4
	Stakes	2	2	2	3
Adjacent ecosystem resilience	Coral reefs	4	4	4	3
	Sea grass	2	2	2	3
Climate (rainfall) modeling <sup>7</sup>	Available projections	3	2	1	2
Local community knowledge	Workshops and questionnaires	2	2	3	5

**Table 24. Relative comparison of the different VA components. Note that cost is scale-dependent upon the size of the mangrove forest. Key to scales: 1–Low; 2–Some; 3–Moderate; 4–Rather high; 5–High**

<sup>5</sup> Refers just to use of the data from and not the setup and maintenance of a tide gauge or climate model – which are high-technology and expensive, and need lengthy data sets.

<sup>6</sup> Some sites can be difficult to interpret; others are very clear.

<sup>7</sup> See footnote 5.

## 4.0 Interpreting a Vulnerability Assessment

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This section explains how to combine results from some or all of the eight components described in Section 3 to obtain an overall vulnerability assessment for a given mangrove area. The information must be synthesized to identify levels of resilience or vulnerability. From this synthesis, appropriate adaptation actions, which are described in Section 5, can be identified and prioritized.

Vulnerability is a function of exposure, sensitivity and adaptive capacity (Figure 4). The reduction of exposure and sensitivity also contributes to greater adaptive capacity. The eight components outlined in Section 3 allow the assessment of sensitivity, exposure and adaptive capacity for a given mangrove area. Note that impact identification indicates any sensitivity to date.

Vulnerability is not an absolute quantitative characteristic. It is a relative, non-measurable, dimensionless property (Stigter et al., 2006). Vulnerability of ecosystems to individual threats has been ranked for a number of ecosystems through surveys of relevant experts (Halpern et al., 2007; Halpern et al., 2008; Selcoe et al., 2009; Teck et al., 2010; Fuentes et al., 2011; Grech et al., 2011). These online surveys were sometimes impressionistic. For example, the risk of exposure of turtle breeding grounds in Queensland, Australia, to sea level rise was ranked as “never occurs/occasionally/often or constant” by sea turtle experts (Fuentes et al., 2011), though the survey did not refer to specific sea level change or tide gauge data.

Such online surveys of expert opinion do not practically suit a site-based vulnerability assessment, where risk assessment data are used to guide on-the-ground planning and management. A risk ranking system, however, could identify aspects of the mangrove forest system most susceptible to disturbance under a changing climate (Dale et al., 2001).

### 4.1 Ranking the results

Guidance is given throughout Section 3 on how to rank the results from each VA component using a five-point scale. The “How to analyze results” and “How to interpret vulnerability” subsections under each component can be used to determine a rank score that goes into the last column (S = score). In some cases, that number comes directly from the assessment method; for instance, in the mangrove condition assessment, the scores are determined using Table 6.

To obtain an overall mangrove vulnerability assessment ranking, the scores assigned for each of the eight components in Section 3 should be collated into a single table, as shown in Table 25. The table is divided into exposure, sensitivity and adaptive capacity factors. Tidal range, relative sea level trends, sediment supply rates and precipitation change are all exposure factors, while sensitivity factors include the majority of measured factors, such as forest condition and growth. Availability of migration areas inland from mangroves, community management capacity and degree of stakeholder involvement in mangrove management are adaptive capacity factors.

To obtain the overall score for a given site, add up the scores recorded in the final S column and fill in the total at the bottom of the table. Then divide by the number of completed components of the VA (e.g., the number of rows that were filled in). Some studies will not be able to complete all components of the VA, due to limited budgets or other factors – for example, a mangrove site may not have adjacent coral reefs or sea grass.

#### 4.0 Interpreting a Mangrove Vulnerability Assessment

Rank	1	2	3	4	5	S
<b>Exposure factors</b>						
Tidal range	>3 m	2–3 m	1.5–2.0 m	1–1.5 m	<1 m	
Relative sea level rise (RSLR)	Site uplifting	Site slightly uplifting	Site stable	Site slowly subsiding	Site rapidly subsiding	
Sediment supply rate	High	Fairly high	Medium	Fairly low	Low	
Precipitation change	Becomes wetter	Rainfall unchanged	Somewhat drier	Moderately drier	Significantly drier	
<b>Sensitivity factors</b>						
Mangrove condition	No or slight impact	Moderate impact	Rather high impact	High impact	Severe impact	
Mangrove basal area (m <sup>2</sup> per hectare )	>25	15–25	10–15	5–10	<5	
Basal area change	Positive	No change	Slightly negative	Moderately negative	Highly negative	
Recruitment	All species producing seedlings	Most species producing seedlings	Some species producing seedlings	Just a few seedlings	No seedlings	
Mortality	<4%	4–10%	10–20%	20–30%	>30%	
Litter productivity	High, including >20% fruits and flowers	Medium, including 5–20% fruits or flowers	Medium, with few fruits or flowers	Low (excluding wood)	Mainly wood	
Seaward edge retreat	None	Some	Moderate	Significant	Very significant	
Reduction in mangrove area	None or little	Some	Moderate	Significant	Very significant	
Elevations within mangroves	Zone brackets 60 cm +	Zone brackets 50–60 cm	Zone brackets 30–50 cm	Zone brackets 20–30 cm	Zone brackets <20 cm	
Sedimentation rates in mangroves	> 1 mm greater than RSLR	< 1 mm greater than RSLR	Equal to RSLR	< 1 mm less than RSLR	> 1 mm less than RSLR	
Adjacent coral reef resilience	Very high	High	Moderate	Low	Very low	
Adjacent sea grass resilience	Very high	High	Moderate	Low	Very low	
Mangrove protection legislation	Good	Fairly good	Moderate	Poor	None	
<b>Adaptive capacity factors</b>						
Elevations above mangroves	Migration areas very available	Migration areas mostly available	Some migration areas available	Few migration areas available	No migration areas available	
Community management capacity	Good	Fairly good	Moderate	Poor	None	
Stakeholder involvement	Good	Fairly good	Moderate	Poor	None	
<b>Total</b>						

**Table 25. Ranking worksheet for mangrove vulnerability assessment results.**

$$\text{Vulnerability score} = \frac{\text{Total Score}}{\text{Number of rows filled}}$$

## 4.2 Interpreting the vulnerability rank

The final overall score from Table 25 is the overall site vulnerability score, where 1 is low vulnerability and 5 is very high vulnerability.

Rank	1	2	3	4	5
Vulnerability	Low	Some	Moderate	High	Very high

Mangrove areas with scores of 4 to 5 have low resilience and high vulnerability and are unlikely to adapt to climate change impacts without significant and immediate interventions. Mangrove areas with a score of 3 have moderate vulnerability, with some core vulnerabilities that targeted interventions could reduce. Mangrove areas with scores of 1 to 2 currently have good resilience, which can be further enhanced by taking actions to reduce the scores of any individual VA components that are higher than 1.

Higher scores in the “Contribution to the VA” column in Table 24 show the relative importance of those components to the overall vulnerability assessment. These values were determined from experience during the WWF pilots. We considered a calculated weighting

of these more critical components, but found it best to keep the calculation simple as the score is indicative in identifying vulnerability and resilience and in prioritizing adaptation activities (Section 5). In Table 25, these more critical components do, however, obtain a weighting by more than one score being related to that component.

The most critical components of the vulnerability assessment are those that help to assess the exposure factors of relative sea level trends and sediment supply and the sensitivity factors of forest condition and growth, recent spatial change and sedimentation rates. These are the “tipping point” factors for a mangrove ecosystem, whereas the other factors are less critical. Local community knowledge is an indicator of social vulnerability, rather than a direct measure of ecosystem vulnerability, and also scores highly.

If a particular component was carried out and resulted in a low vulnerability score, such as good mangrove condition, positive tree growth or no seaward edge retreat, this resilience can be celebrated but it should be monitored in future to detect any change in condition. Ongoing monitoring is discussed further in subsection 5.3.

### Case studies

Overall score ranking results derived from Table 25 are provided below for the three WWF pilot sites. Some of these scores are explained in detail in the case studies in Section 3. Where a row is blank, either this component was not carried out for that site, or the results were inconclusive. The calculation of the overall vulnerability score is demonstrated for each site, and comments are given on how that score can be reduced through specific adaptation actions. These actions are explained in detail in Section 5.

Table 26. Vulnerability ranking of Douala Estuary, Cameroon.

Rank	1	2	3	4	5	S
<b>Exposure factors</b>						
Tidal range	>3 m	2–3 m	1.5–2.0 m	1–1.5 m	<1 m	4
Relative sea level rise (RSLR)	Site uplifting	Site slightly uplifting	Site stable	Site slowly subsiding	Site rapidly subsiding	3
Sediment supply rate	High	Fairly high	Medium	Fairly low	Low	2
Precipitation change	Becomes wetter	Rainfall unchanged	Somewhat drier	Moderately drier	Significantly drier	
<b>Sensitivity factors</b>						
Mangrove condition	No or slight impact	Moderate impact	Rather high impact	High impact	Severe impact	2
Mangrove basal area (m <sup>2</sup> per hectare )	>25	15–25	10–15	5–10	<5	2
Basal area change	Positive	No change	Slightly negative	Moderately negative	Highly negative	1
Recruitment	All species producing seedlings	Most species producing seedlings	Some species producing seedlings	Just a few seedlings	No seedlings	2
Mortality	<4%	4–10%	10–20%	20–30%	>30%	1
Litter productivity	High, including >20% fruits and flowers	Medium, including 5–20% fruits or flowers	Medium, with few fruits or flowers	Low (excluding wood)	Mainly wood	
Seaward edge retreat	None	Some	Moderate	Significant	Very significant	2
Reduction in mangrove area	None or little	Some	Moderate	Significant	Very significant	1
Elevations within mangroves	Zone brackets 60 cm +	Zone brackets 50–60 cm	Zone brackets 30–50 cm	Zone brackets 20–30 cm	Zone brackets <20 cm	3
Sedimentation rates in mangroves	> 1 mm greater than RSLR	< 1 mm greater than RSLR	Equal to RSLR	< 1 mm less than RSLR	> 1 mm less than RSLR	3
Adjacent coral reef resilience	Very high	High	Moderate	Low	Very low	
Adjacent sea grass resilience	Very high	High	Moderate	Low	Very low	
Mangrove protection legislation	Good	Fairly good	Moderate	Poor	None	3
<b>Adaptive capacity factors</b>						
Elevations above mangroves	Migration areas very available	Migration areas mostly available	Some migration areas available	Few migration areas available	No migration areas available	3
Community management capacity	Good	Fairly good	Moderate	Poor	None	2
Stakeholder involvement	Good	Fairly good	Moderate	Poor	None	2
<b>Total</b>						<b>36</b>

$$\text{Vulnerability score} = \frac{36 \text{ (total score)}}{16 \text{ (number of rows)}} = 2.3$$

The Douala Estuary mangroves of Cameroon have overall resilience but some inherent vulnerability due to the low tidal range of the area. Vulnerability can be reduced by addressing the non-climate stressors on the mangrove area, particularly those resulting from human impacts, and by fostering management actions

that enhance sedimentation. Priorities for adaptation planning in mangrove areas that are located in such low tidal range regions are to plan inland migration areas and strategic protected areas for mangroves, and to undertake management activities that enhance accretion within the mangroves.

Table 27. Vulnerability ranking of Rufiji Delta, Tanzania.

Rank	1	2	3	4	5	S
<b>Exposure factors</b>						
Tidal range	>3 m	2–3 m	1.5–2.0 m	1–1.5 m	<1 m	1
Relative sea level rise (RSLR)	Site uplifting	Site slightly uplifting	Site stable	Site slowly subsiding	Site rapidly subsiding	2
Sediment supply rate	High	Fairly high	Medium	Fairly low	Low	2
Precipitation change	Becomes wetter	Rainfall unchanged	Somewhat drier	Moderately drier	Significantly drier	2
<b>Sensitivity factors</b>						
Mangrove condition	No or slight impact	Moderate impact	Rather high impact	High impact	Severe impact	1
Mangrove basal area (m <sup>2</sup> per hectare )	>25	15–25	10–15	5–10	<5	2
Basal area change	Positive	No change	Slightly negative	Moderately negative	Highly negative	1
Recruitment	All species producing seedlings	Most species producing seedlings	Some species producing seedlings	Just a few seedlings	No seedlings	1
Mortality	<4%	4–10%	10–20%	20–30%	>30%	1
Litter productivity	High, including >20% fruits and flowers	Medium, including 5–20% fruits or flowers	Medium, with few fruits or flowers	Low (excluding wood)	Mainly wood	
Seaward edge retreat	None	Some	Moderate	Significant	Very significant	2
Reduction in mangrove area	None or little	Some	Moderate	Significant	Very significant	3
Elevations within mangroves	Zone brackets 60 cm +	Zone brackets 50–60 cm	Zone brackets 30–50 cm	Zone brackets 20–30 cm	Zone brackets <20 cm	
Sedimentation rates in mangroves	> 1 mm greater than RSLR	< 1 mm greater than RSLR	Equal to RSLR	< 1 mm less than RSLR	> 1 mm less than RSLR	1
Adjacent coral reef resilience	Very high	High	Moderate	Low	Very low	2
Adjacent sea grass resilience	Very high	High	Moderate	Low	Very low	
Mangrove protection legislation	Good	Fairly good	Moderate	Poor	None	1
<b>Adaptive capacity factors</b>						
Elevations above mangroves	Migration areas very available	Migration areas mostly available	Some migration areas available	Few migration areas available	No migration areas available	1
Community management capacity	Good	Fairly good	Moderate	Poor	None	4
Stakeholder involvement	Good	Fairly good	Moderate	Poor	None	3
<b>Total</b>						<b>30</b>

$$\text{Vulnerability score} = \frac{30}{17} = 1.8$$

The Rufiji Delta has some inherent resilience, having a higher tidal range than Cameroon or Fiji and being fed by a major river with high sediment inputs, while apparently experiencing slight tectonic uplift. The river catchment is not currently predicted to receive

reduced rainfall as a result of climate change, although there is uncertainty. Much of the delta is also relatively sheltered from storm effects by a large offshore island (Mafia Island). While GIS analysis and forest assessment results showed resilience in the majority of the mangrove area, including seaward sections, there have been losses of mangroves on the landward

margins owing to human disturbance, particularly from the conversion of mangrove habitat for rice cultivation.

The main source of vulnerability comes from this relatively high human disturbance; and, in the event of future sea level rise, this may restrict the capacity of mangroves to retreat inland even though elevations

there would normally permit mangrove migration. The vulnerability of the mangrove areas in the Rufiji Delta can be reduced through further efforts by local communities and other stakeholders to improve mangrove management capacity and reduce human impacts there.



Photo: Joanna Ellison



Photo: Michael Case

Table 28. Vulnerability ranking of Tikina Wai, Fiji.

Rank	1	2	3	4	5	S
<b>Exposure factors</b>						
Tidal range	>3 m	2–3 m	1.5–2.0 m	1–1.5 m	<1 m	4
Relative sea level rise (RSLR)	Site uplifting	Site slightly uplifting	Site stable	Site slowly subsiding	Site rapidly subsiding	4
Sediment supply rate	High	Fairly high	Medium	Fairly low	Low	3
Precipitation change	Becomes wetter	Rainfall unchanged	Somewhat drier	Moderately drier	Significantly drier	
<b>Sensitivity factors</b>						
Mangrove condition	No or slight impact	Moderate impact	Rather high impact	High impact	Severe impact	1
Mangrove basal area (m <sup>2</sup> per hectare )	>25	15–25	10–15	5–10	<5	1
Basal area change	Positive	No change	Slightly negative	Moderately negative	Highly negative	1
Recruitment	All species producing seedlings	Most species producing seedlings	Some species producing seedlings	Just a few seedlings	No seedlings	1
Mortality	<4%	4–10%	10–20%	20–30%	>30%	1
Litter productivity	High, including >20% fruits and flowers	Medium, including 5–20% fruits or flowers	Medium, with few fruits or flowers	Low (excluding wood)	Mainly wood	1
Seaward edge retreat	None	Some	Moderate	Significant	Very significant	1
Reduction in mangrove area	None or little	Some	Moderate	Significant	Very significant	1
Elevations within mangroves	Zone brackets 60 cm +	Zone brackets 50–60 cm	Zone brackets 30–50 cm	Zone brackets 20–30 cm	Zone brackets <20 cm	3
Sedimentation rates in mangroves	> 1 mm greater than RSLR	< 1 mm greater than RSLR	Equal to RSLR	< 1 mm less than RSLR	> 1 mm less than RSLR	2
Adjacent coral reef resilience	Very high	High	Moderate	Low	Very low	1
Adjacent sea grass resilience	Very high	High	Moderate	Low	Very low	3
Mangrove protection legislation	Good	Fairly good	Moderate	Poor	None	3
<b>Adaptive capacity factors</b>						
Elevations above mangroves	Migration areas very available	Migration areas mostly available	Some migration areas available	Few migration areas available	No migration areas available	3
Community management capacity	Good	Fairly good	Moderate	Poor	None	1
Stakeholder involvement	Good	Fairly good	Moderate	Poor	None	1
<b>Total</b>						<b>36</b>

$$\text{Vulnerability score} = \frac{36}{19} = 1.9$$

The mangrove areas of Tikina Wai, Fiji, have inherent vulnerability due to the low tidal range and the subsiding coastline of the area. However, the area scores fairly low because of its relatively high sedimentation rates and the strong involvement of local communities in mangrove, sea grass and reef management. Vulnerability

can be reduced by further enhancing local management capacity to reverse declines in sea grass cover at near-shore sea grass habitats and by controlling human pressures, such as ash fallout from sugarcane burning. The vulnerability of the Tikina Wai mangroves can be further reduced by better planning of migration areas inland and by working with the government to improve mangrove-related protection legislation.

# 5.0 Developing Adaptation Measures

The vulnerability assessment synthesis (Section 4) gave an overall vulnerability ranking that resulted from the contribution of individual scores from each VA component. Those individual scores can help in selecting and prioritizing among a range of potential adaptation strategies.

Table 29 links the rank factors from Table 25 with some of the potential adaptation actions that can be carried out to reduce any higher vulnerability scores. The results from Table 25 should be reviewed; where a vulnerability score is higher than 1, the corresponding row in Table 29 can be used to identify adaptation actions to reduce that vulnerability. These actions are

explained in the following subsections.

The ranking of some exposure factors, such as tidal range and relative sea level trends, cannot be reduced, but identified actions can improve adaptive capacity to deal with those factors. The ranking of most sensitivity factors can be reduced, however.

These adaptation actions are described in the following subsections, where they are reordered from Table 29 into these logical groupings:

- Subsection 5.1: Reduction of non-climate stressors
- Subsection 5.2: Active adaptation actions
- Subsection 5.3: Monitoring and evaluation

Higher rank factor	Adaptation actions	Subsection
Tidal range	Plan inland migration areas	5.2.2
	Establish strategic protected areas	5.1.3
	Manage for accretion in mangroves	5.2.1
Relative sea level rise (RSLR)	Manage for accretion in mangroves	5.2.1
	Plan inland migration areas	5.2.2
Sediment supply rate	Manage for accretion in mangroves	5.2.1
Precipitation change	Rehabilitate degraded mangroves	5.1.4
Mangrove condition	Reduction of non-climate stressors Improve local management Establish strategic protected areas Improve legislation Rehabilitate degraded mangroves Plan inland migration areas	5.1
Mangrove basal area		5.1.1
Basal area change		5.1.3
Recruitment		5.1.2
Mortality		5.1.4
Litter productivity		5.2.2
Seaward edge retreat	Manage for accretion in mangroves Plan inland migration areas	5.2.1
Reduction in mangrove area		5.2.2
Elevations within mangroves	Manage for accretion in mangroves	5.2.1
	Plan inland migration areas	5.2.2
Elevations above mangroves	Plan inland migration areas	5.2.2
Sedimentation rates in mangroves	Manage for accretion in mangroves	5.2.1
Adjacent coral reef resilience	Reduction of non-climate stressors	5.1
	Rehabilitation (of reefs)	(a)
Adjacent sea grass resilience	Reduction of non-climate stressors	5.1
	Rehabilitation (of sea grass)	(b)
Community management capacity	Improve local management	5.1.1
Stakeholder involvement	Improve legislation	5.1.2
	Improve local management	5.1.1
Mangrove protection legislation	Improve legislation	5.1.2

**Table 29. Adaptation actions to reduce vulnerability ranking, with reference to subsections further describing each action. Additional resources are (a) Marshall & Schuttenberg (2006), Grimsditch & Salm (2006) and (b) Björk et al. (2008).**

The overall objective of the actions described in all three subsections is the enhancement of mangrove resilience to climate change through the reduction of vulnerability.

### Enhancement of mangrove resilience

Ecosystem resilience is the ability of a system to maintain key functions and processes in the face of stresses or pressures by either resisting or adapting to change (Hansen et al., 2003; Marshall & Schuttenberg, 2006). Mangrove ecosystems can be resilient to climate change if they are healthy, with high diversity and active sedimentation processes and if there are inland migration areas available at suitable elevations. People living in and around mangroves can help them adapt to climate change by implementing management practices that enhance these mangrove values, and by reducing their own pressure on mangrove resources.

Hence adaptation can include actions to reduce vulnerability or enhance resilience (Adger et al., 2007). Adaptation options to increase the resistance and resilience of mangroves to climate change have been reviewed by McLeod and Salm (2006), Gilman et al. (2006a), Gilman et al. (2006b), Lovelock and Ellison (2007), Gilman et al. (2008), Gehrke et al. (2011) and Waycott et al. (2011). The adaptation actions described in this section have been selected from those recommended in these and other reviews. They are presented as a set of targeted options that can directly reduce the specific vulnerabilities identified in Section 4.

Monitoring and evaluation is essential as an ongoing action, as it will facilitate identification of climate change impacts and adjustment of management priorities. While not explicitly featured in Table 29, it should be an overall priority.

People living in mangrove areas and dependent on natural resources, such as those in the WWF pilot areas in Cameroon, Tanzania and Fiji, tend to plan in time frames of weeks to months and up to a year; whereas climate change threats 10 to 20 years in the future are generally less of a priority. One way to reconcile this issue is to promote win-win or “no regrets” strategies: adaptation actions that improve current resource conditions as well as decrease climate change vulnerability and are not likely to result in future maladaptation, which could undermine the adaptive capacity of both the community and the mangroves.

These actions increase mangrove resilience.

One question has been whether people or ecosystems do the adapting, and our answer is both. Adaptability refers to the degree to which adjustments can be made in practices, processes, community structures or systems in response to projected or actual changes in climate (Adger et al., 2007; Mertz et al., 2009). In this context, adaptive capacity is the ability of a mangrove ecosystem and the people living there to adjust to climate change (including climate variability and extremes) – to moderate potential damages, take advantage of opportunities and/or deal with consequences. The actions discussed in the following subsections are what those managing mangrove ecosystems can do to enhance those mangroves’ capacity to adapt to sea level rise impacts, in particular, but also to enhance the capacity of people living nearby to assist in this process.

## 5.1 Reduction of non-climate stressors

Reduction of non-climate stressors increases the resilience of habitats and species to the effects of climate change and variability (Erwin, 2009), and correspondingly, the vulnerability to climate change of natural resource-dependent communities is increased if their resource base is degraded by overuse or if their management systems are ineffective (Adger et al., 2007). This is the case for many mangrove areas where communities are largely dependent on mangrove resources, such as fish, crustaceans and fuelwood and unsustainable use can reduce mangrove resilience. Hence, a key adaptation response is improved management, education and awareness-building as well as greater community involvement in mangrove area management. Reduction of non-climate stressors may also enhance ecosystem productivity, which has been shown to cause elevation gain of tidal wetlands (Langley et al., 2009).

The adaptive capacity of a mangrove system can be increased by improvement in mangrove condition as identified in subsection 3.2. Where the condition of mangroves is already degraded, climate change is anticipated to make conditions worse, thereby adding a level of urgency to the need to take action to better protect and/or rehabilitate these ecosystems. This can be done by reducing existing human impacts on mangroves and by rehabilitating damaged areas.

### 5.1.1 Improve local management

The key to the protection of coastal wetlands such as mangroves is engagement of local communities in their sustainable management, facilitated by accessible technical support and effective legislation (Ellison, 2009b). Community support for adaptation actions can be improved by education and capacity building, which are core tasks for many conservation institutions and agencies. Education and outreach programs are an investment to bring about changes in attitudes and behavior and attitudes by having a community that is better informed about the value of mangroves and associated ecosystems. Such an increase in public knowledge of the importance of mangroves helps a community to make more informed decisions about the use of their mangrove resources, and results in grass-roots support and increased political will for measures to conserve and sustainably manage mangroves.

Awareness-building and education of community members improves the sustainable use of mangrove resources, helps to reduce direct human impacts and builds capacity to adapt to climate change. These actions can be carried out through meetings, workshops, reconnaissance surveys of the mangroves that involve community members and a range of other engagement activities.

Community awareness-building is generally best focused on the following actions:

- Demonstrating mangrove values to the community: The mangrove values concept diagram (Figure 2) and supporting information can be used or adapted.
- Explaining sustainable use of mangroves: The mangrove condition assessment and identification of impacts from subsection 3.2.1 can be used.
- Climate change adaptation actions from elsewhere in Section 5, particularly mangrove rehabilitation.

Increasing awareness can use approaches that are adaptable, opportunistic and guided by the culture and history of engagement in the area. In Fiji, this was facilitated through the traditional welcome and farewell ceremonies of the villages as various WWF



Photo: Jonathan Cook

Figure 46. Traditional welcome ceremony at Tikina Wai, Fiji.

project staff visited to carry out work. During these ceremonies, the chair of the Tikina Wai Resource Management Committee and the village chief made speeches to community members about the goals of the project and the importance of the mangroves (Figure 46), which were also featured in media coverage.

In Tanzania, after awareness meetings had begun in Rufiji Delta villages, local football teams offered to help build awareness in exchange for the sponsorship of footballs and shirts. The teams took short charity walks around a village (Figure 47) singing songs, including –



Photo: Frank Sima

Figure 47. Homeboys Football club jogging and singing a mangrove song in a Rufiji Delta village (from Sima, 2010).

“Let’s keep the mangroves to rectify ongoing global change.”

“Mangroves help keep cool temperatures [which are] good for football playing.”

“Let’s participate [in] mangrove protection and replant degraded areas.”

### 5.1.1.1 Reduce human impacts on mangroves

Human pressure on mangroves (for example, through the gathering of food or fuelwood) has been reduced by many conservation practitioners through working with local communities and building their capacity to improve local management and planning. For example, WWF has worked with communities in Tikina Wai, Fiji, since the late 1990s to establish three community mangrove reserves. These reserves are checked by village monitors and managed by a marine resource committee with representatives from six villages. Village surveillance and monitoring enables feedback to the committee on any resource abuse or decline in fish or crab availability, and management decisions are made on this basis.

Reduction of human impacts on mangroves is part of a “no regrets” strategy of improved management. In Cameroon, the local communities depend on mangrove wood as a fuel for cooking and smoking seafood and to provide poles for construction; and that wood is often gathered from unsuitable areas (Figure 48). Mangrove wood gathering zones have now been designated, particularly excluding mangroves that are on or near the seaward edge or on the margins of creeks and waterways.

Also in Cameroon, WWF has supported the development of more efficient ovens for wood smoking. Open fires are an inefficient cooking method with high losses of energy (Figure 49). Low-cost fish smokehouses (Figure 50) have been developed that use up to 75 percent less wood compared with open fires, thereby substantially decreasing cooking time and also reducing fumes that can cause human health problems. These smokehouses have been introduced to a number of mangrove-associated communities, providing communal facilities for village use.



Photo: Joanna Ellison

**Figure 48.** Mangrove poles cut from a creek margin in Cameroon. This is the worst place to cut since mangrove margins are the least resilient areas, but unfortunately these areas are often the most accessible.



Photo: Joanna Ellison

**Figure 49.** Low-efficiency open fire cooking of shellfish, Cameroon.



Photo: Joanna Ellison

**Figure 50.** Improved-efficiency wood smokehouses for cooking fish and shellfish, Cameroon.

### 5.1.1.2 Foster mangrove green shields

Specific mangrove areas identified by GIS analysis (subsection 3.3) or by the community as particularly affected, either by overexploitation or natural erosion, are often located close to village areas. These areas can be prioritized for rehabilitation and designated as “green-shield” belts that protect the village from storms. Such a designation helps to prioritize a given area for replanting, encourages reduced impact by community members, and provides a convenient local example for ongoing monitoring and capacity building in the community.

Specific information on replanting and rehabilitation of mangroves is given in subsection 5.1.4.

### 5.1.2 Improve legislation

The engagement of local communities in the sustainable management of mangrove areas is absolutely indispensable, but this must also be supported by government legislation that protects mangrove ecosystems. Enforcement of existing legislation also needs to be effective. The WWF pilots in Cameroon, Tanzania and Fiji found that policies to protect mangroves are frequently weak or fragmented into a set of nonspecific laws that are administered by a range of government departments lacking the resources to properly implement them.

Such weak or vague legislation for the sustainable use and protection of mangroves needs to be identified and improved, and conservation practitioners can assist in this process through ongoing stakeholder discussions, lobbying and advocacy. There is a continuing need for building capacity in many management agencies, including the capacity to enforce legislation and a general understanding of mangrove vulnerability and adaptation. There is often a lack of consideration of the impacts of upstream development on downstream mangroves. Wetlands such as mangroves are often used without zoning for different levels of usage and protection or monitoring of sustainable use. Better management happens in community-based conservation areas where local committees can close areas or restrict their use, based on the state of resources.

Using results derived from the vulnerability assessment, conservation practitioners can provide informed recommendations for legislative reform to the relevant stakeholders. VA sections that will have the most relevant results are

- forest assessment results showing human impacts
- GIS results showing human impacts
- local community knowledge and survey results showing a need for changes to management approach and/or legislation

Community and stakeholder involvement is an overarching principle of the vulnerability assessment process (subsection 2.4), and the sharing of results from the vulnerability assessment with stakeholders may help to support the case for legislative improvement. Such improvement can be facilitated by expert review of environmental legislation such as that carried out by the GEF International Waters Project in the Pacific Islands (Tavala & Hakwa, 2004; Powell, 2004; Powell, 2006; Evans, 2006).

At the local level, policy for improved mangrove management proved successful in the WWF pilots through the participation of local communities in establishing mangrove resource management committees which monitor and control mangrove resource use. Improved management was helped by consultation and dialogue with key stakeholders such as local administration, local councils and local government departments, especially forestry, environment and fisheries.

### 5.1.3 Establish strategic protected areas

Protected areas support key centers of biodiversity and provide refuges for wildlife. It is important to designate areas that are likely to be resilient to climate change. Mangroves are frequently underrepresented ecosystem types in marine protected areas (Pomeroy et al., 2007). Mangrove protected areas that are strategic choices in light of climate change are those that have a good sediment supply and high species diversity, as both of these factors enhance resilience; as well as those areas that score low on the vulnerability ranking in Section 4, particularly in the forest condition and spatial change sections (subsections 3.2 and 3.3).

The forest assessment section uses the same basal area and biomass monitoring methods recommended for evaluation of the success of protected area management (Pomeroy et al., 2007).

Long-term planning of strategic protected areas is improved if these areas have designated inland migration areas defined by elevation for sea level rise of up to 1 m and more. These can be identified using the methods described in subsection 3.4.1. Also, larger reserves better ensure representation of all mangrove community types to spread risk and increase chances for mangrove ecosystems to adapt to climate change and other stresses (Julius & West, 2008; Gilman et al., 2008). Areas that have a microtidal range have unique mangrove settings that are important to protect; and, although they have higher exposure to sea level rise, their vulnerability can be reduced by adaptation actions that reduce other vulnerability rankings.

Community-managed protected areas also enhance the resilience of mangroves to climate change through the reduction of non-climate stressors and community surveillance of changes over time. Tikina Wai in Fiji (Figure 51) demonstrates the effectiveness of such protected areas, which have been established there for nearly 10 years and led to improvements in mangrove ecosystem health and productivity (Table 7).

The community-managed protected areas of Tikina Wai encompass mangroves in the Lotonaluya, Bole and Lomawai protected areas and adjacent ecosystems of coral reefs and sea grass in the marine protected areas offshore. Such protected areas safeguards connectivity and functional links between associated coastal ecosystems (Crowder et al., 2000; Stewart et al., 2003; Roberts et al., 2003; Gilman et al., 2008). Protecting a series of mature, healthy mangrove sites along a coastline increases the availability of a diverse source

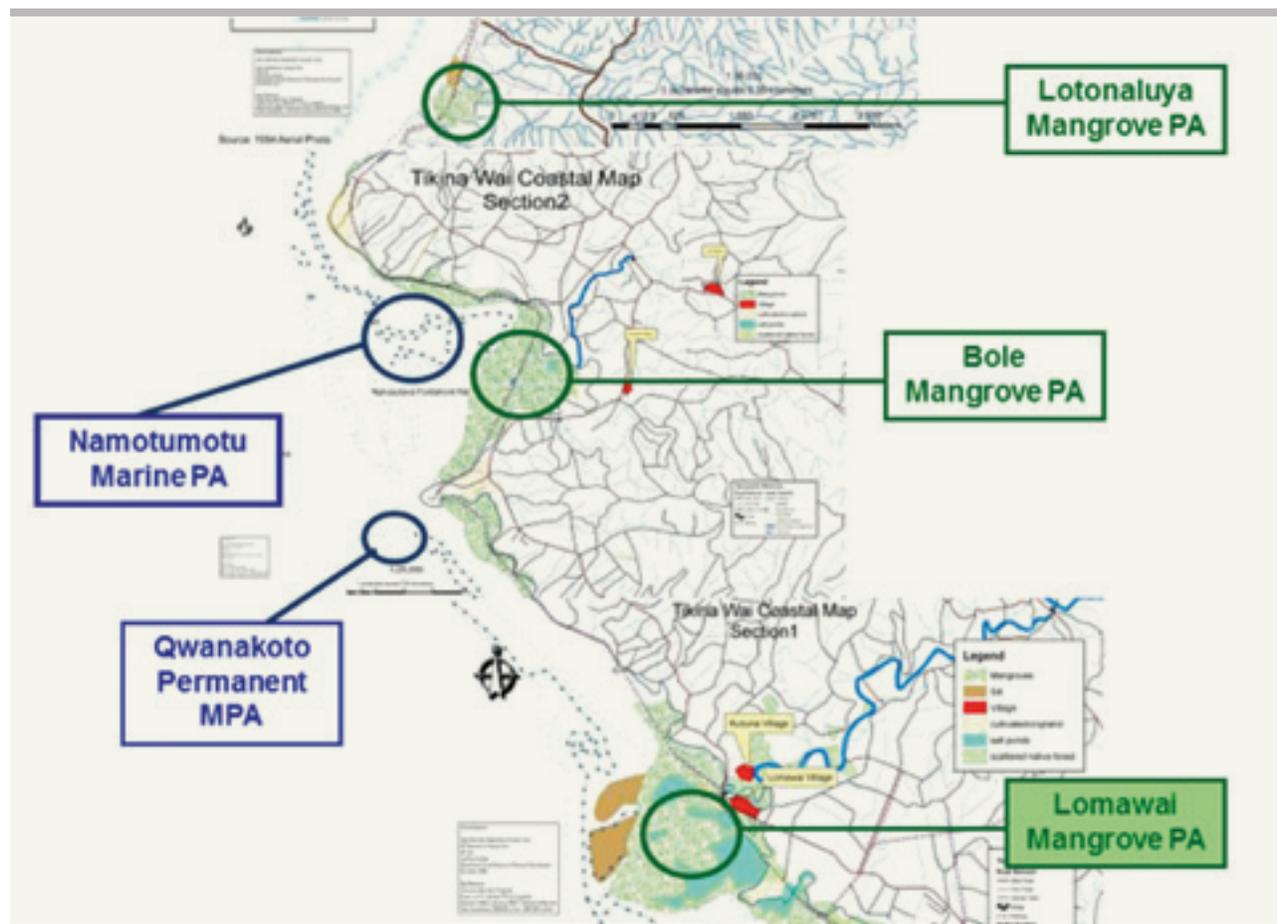


Figure 51. Community-managed protected areas, Tikina Wai, Fiji (Fiu et al., 2010).

of seeds and hypocotyls to recolonize other sites that are degraded.

These protected areas are monitored by Tikina Wai community members who observe mangrove and sea grass conditions (subsections 3.2.1 and 3.8.2) and report back to a natural resource management committee. An adjacent dive shop, Scuba Bula, assists WWF divers in monitoring seawater temperatures at the offshore marine protected areas and reports back on reef health, fish abundance and temperature trends using coral reef monitoring methods (subsection 3.8.1). These activities provide information on the area's resistance and resilience to resource usage and possible impacts of sea level rise and other climate-related changes.

### 5.1.4 Rehabilitate degraded mangroves

Rehabilitation of degraded mangrove areas will likely be one of the most effective strategies for building resilience, particularly where sections of an otherwise healthy system are degraded. Mangroves that are degraded are more likely to show impacts from climate change effects than mangroves that are healthy (McKee et al., 2007). Healthy mangroves promote higher levels of sediment accretion and land building, while degradation of mangroves can cause coastal erosion. Dense seedlings also enhance sediment accretion (Huxham et al., 2010; Kumara et al., 2010).

Impacted or degraded mangrove locations within a particular forest area can be identified through rapid assessment (subsection 3.2.1), GIS evidence of forest decline (subsection 3.3) and compilation of local community knowledge (subsection 3.9).

There is a wealth of experience in mangrove reforestation, restoration and replanting in many countries (Agaloo, 1994; Hong, 1994; Chan, 1996; Biswas et al., 2009) that can be used to help enhance adaptive capacity. One successful example is a community forest at Yadfon in Thailand, where a committee of 10 to 20 people guided mangrove

replanting as part of a larger cooperative program to help fishing people sell catch and purchase fishing equipment (Quarto, 1999). The project recognized the knowledge of the local fishers and the lack of economic opportunities. Within two months of replanting mangroves, the villagers began noticing an increase in their near-shore fish catch and the appearance of fish species that had previously been rare. This example shows that, in a rehabilitation project, it is necessary to engage the support of the local community that has traditional use of the mangrove area and to engage the support of other interested stakeholders.

A further successful example comes from the Upper Gulf of Thailand where, following coastal erosion, the Thai government approved a national mangrove management plan in 1987 that included funding of a mangrove rehabilitation project (Winterwerp et al., 2005). Beneficial effects of rehabilitation included an increase of sediment capture and stabilization, an increase of habitat for species such as crabs and coastal fisheries, an increase of resting and feeding habitat for migratory and local birds and increased resilience to sea level rise and climate change. This further demonstrates the “win-win” or “no regrets” potential of mangrove rehabilitation.<sup>8</sup>

Although there is increasingly good Internet coverage of mangrove replanting activities, such as the Mangrove Action Project (2006) guide, there have been unsuccessful projects where most or all seedlings have died (reviewed by Lewis, 2005). To promote success, a number of considerations are outlined in the following subsections, using examples from the WWF pilots (Sima, 2010). Successful replanting involves a sequence of potential activities shown in Figure 52.

<sup>8</sup> An excellent example of community-based coastal restoration is the Green Coast project: <http://www.wetlands.org/Default.aspx?TabId=436&language=en-US>

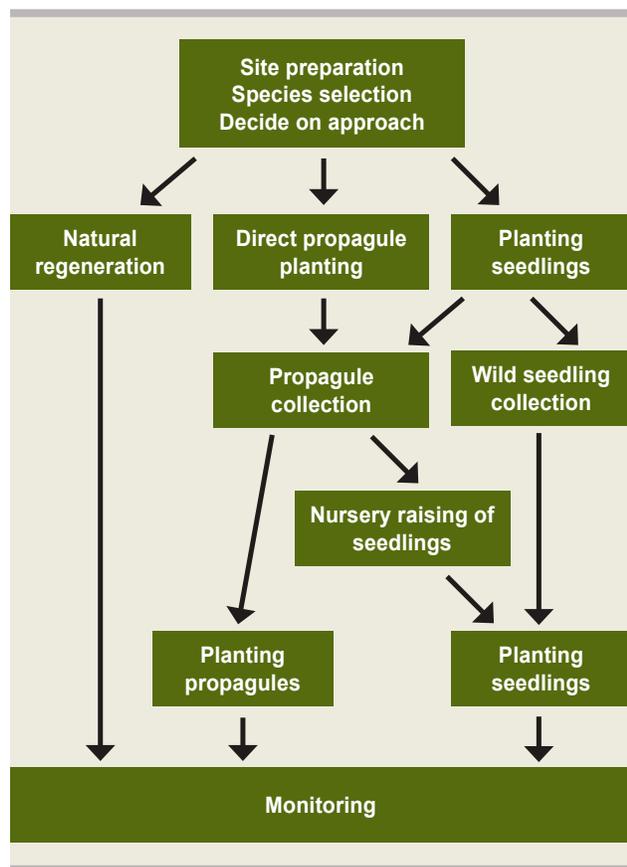


Figure 52. Flowchart of potential approaches to mangrove rehabilitation.

#### 5.1.4.1 Selection of “climate-smart” mangrove species

Understanding the ecology of local species is an important early step in successful mangrove restoration (Bosire et al., 2008), particularly in terms of choosing sites that have suitable hydrological regimes with respect to the frequency and duration of tidal flooding (Figure 21; Mangrove Action Project, 2006; Bosire et al., 2008). Restoration also needs to consider changing future conditions of hydrology and mangrove habitats (Erwin, 2009) in planning areas for replanting and selecting species.

The greatest sensitivity of mangroves to climate change is to relative sea level rise that increases inundation periods. Sea level rise is projected to increase over the lifetime of mangrove trees. Although they can migrate,

they will have to tolerate a continually rising sea level during their lifetime. Therefore, the most resilient species to changing sea level will be those with tolerance of a wider elevation bracket, as identified in subsection 3.4. In the WWF pilots, this was found to be *Rhizophora harissonii* in Cameroon and *Rhizophora stylosa* in Fiji, as shown by the case studies in subsection 3.4.2.

#### 5.1.4.2 Replanting practices

Before rehabilitation, the cause of the original mangrove decline or mortality should be identified and removed when possible (Lewis, 2005; Biswas et al., 2009). This can be informed by the results of the mangrove condition assessment (subsection 3.2.1), GIS analysis (subsection 3.3) and community consultation (subsection 3.9). Impediments to mangrove establishment, such as dead trees, debris, garbage and anything (even palm fronds) that may move around during high tide, should be removed. This is because such loose debris can move at high tide, especially with waves, and knock over planted seedlings. Local communities can assist in ongoing maintenance, including surveillance for other factors that might prevent seedling growth, such as grazing or pig or dog disturbance.

As shown in Figure 52, there are three approaches to mangrove rehabilitation that can be used: natural regeneration, propagule planting or seedling planting.

- Natural regeneration:** This is a nonactive approach that protects and monitors the mangrove area from the original stress and allows natural regeneration to occur. This approach does not usually involve rates that would result in rapid regeneration of the area, and it does not allow species selection.
- Direct propagule planting:** This approach involves active planting of mature mangrove propagules in areas where they might grow. The survival rate of seeds is usually much lower than with seedling planting.
- Seedling planting:** This approach involves active planting of seedlings in areas where they might grow. The seedlings can be obtained from wild sources elsewhere (wild seedling transplanting), or raised in a mangrove nursery.

### 5.1.4.3 Propagule collection

Most mangrove propagules are viviparous (already germinated) and so have to be planted within a few weeks. This is why they are called propagules or hypocotyls, rather than seeds. They cannot be dried and stored like seeds. Vivipary is an adaptation that mangroves have to their wet and saline habitat (Figure 53).

Seeds for planting or raising in nurseries must therefore be collected when they are ripe. If hypocotyls are collected too young, they will not develop (Hong, 1994). Mangrove phenology (the timing of fruiting) is controlled by seasonal patterns, and litter studies (subsection 3.2.3) show when the fruiting times occur — usually in late summer or the wet season.

Maturing or mature propagules of *Rhizophora* can be recognized by the distinct abscission collar between the fruit and the propagule (Figure 53), which is yellow in *R. mucronata* (Chan, 1996). *R. mangle* hypocotyls are ripe when a collar or ring develops at the tip (Banus & Kolehmainen, 1975). *Bruguiera* hypocotyls are ripe when they change color from green to brown; they do not develop an abscission collar. In general, if the hypocotyl does not come off of the parent tree with a slight pull, it is not ripe. *Rhizophora* and *Bruguiera*



**Figure 53.** *Rhizophora stylosa* hypocotyls at the seaward edge in Lomawai, Fiji. The yellow section at the base of the upper brown seed means that these are ready to leave the parent.

hypocotyls must be handled gently, particularly the plumule (first shoot spike) at the top.

Propagules can either be collected from the parent trees or from those that have fallen beneath the trees (Figure 54). Propagules are usually in better condition if collected from the tree, with less physical damage or insect/fungal infestation. They must be unblemished, free from insect attack and handled carefully in transport, Figure 55 shows community members checking their condition. The seeds must not be allowed to dry out; however, if kept in moist conditions they become vulnerable to insect or fungal attack. They cannot be stored for long. It is best to transport and store them in small horizontal bundles, covered with banana leaves, palm fronds or sacking.



**Figure 54.** Collecting mangrove propagules from mangroves within the Rufiji Delta that were planted in 1995 by Tanzania's Forestry and Bee-keeping Division in collaboration with local communities.



**Figure 55. Sorting of healthy seedlings in the Rufiji Delta, informed by the indigenous knowledge of community members.**

#### 5.1.4.4 Planting propagules

Propagules of *Rhizophora* and *Bruguiera* can be planted by gently inserting the tip into a hole poked in the mud, so that one-third to one-half of the propagule length is buried (Figure 56). The propagule should be planted in the same direction as the trajectory of its growth habit, i.e., the same way up as how it hung on the parent tree (Figure 53). Planting can only be done soon after the fruiting season, as mangrove propagules cannot be stored dry for very long.

Figures 57 to 61 show inland mangrove replanting in areas of Tanzania's Rufiji Delta using hypocotyls of *Bruguiera* and *Heritiera*, which are the inland species of this mangrove system. Site preparation included clearing the area of large woody debris and weeds and continued management by the community through weed clearance and cattle exclusion. While the seedling spacing depicted is about 75 cm, more recent studies have shown that increasing seedling density can significantly increase the success of planted species at both low and high tidal sites (Huxham et al., 2010). This practice also enhances sediment accretion



**Figure 56. *Bruguiera gymnorhiza* hypocotyl planted.**

and surface elevation gain that may be crucial to allow mangrove adaptation to rising sea level (Kumara et al., 2010). Huxham et al. (2010) also showed that *Avicennia* has the best survival at high tidal sites owing to its tolerance of higher salinities. It can also act as a nurse species to others, such as *Ceriops*, by changing soil conditions and microclimate.

In Fiji, a Japanese project by the Organisation for Industrial, Spiritual and Cultural Advancement-International (OISCA) has been implemented at Sigatoka on Viti Levu since the mid-



**Figure 57. A mangrove planting group in landward margins of the Rufiji Delta.**



**Figure 58.** A replanted plot in the Rufiji Delta. Ongoing management of this plot included exclusion of cattle grazing to protect the young, tender shoots of growing mangroves.

1990s, raising mangrove seedlings in a nursery and giving them to villages that wish to plant mangroves. Some of these nursery-raised seedlings (as in subsection 5.1.4.6) were sourced and replanted on sand banks offshore of Lomawai (Figure 62). They were *Rhizophora stylosa*, shown in elevation surveys (subsection 3.4.2) to be tolerant of the widest range of substrate elevation, including the lowest elevations at the seaward edge. Due to the location being offshore



**Figure 59.** Rufiji Delta Plot 5 before planting and after planting (inset).

of the mangrove margin on a sand bank, there was subsequent mortality of a number of trees; but some survived, and this will promote further accretion (subsection 5.2.1) to increase the resilience of the mangrove area.



**Figure 60.** Rufiji Delta Plot 7 before preparation and planting.



**Figure 61.** Rufiji Delta Plot 7 after planting.



**Figure 62.** *Rhizophora stylosa* seedlings planted on sand banks offshore of Lomawai, Fiji.

Photo: Joanna Ellison

Seedlings chosen for transplant should be 0.5 to 0.6 m tall, with a straight trunk, an intact growing tip and several leaf pairs. Old seedlings with more than 15 leaf scars on the trunk and those that already have developed prop roots or side branches should not be selected. Older seedlings are less likely to survive transplanting, probably due to root disturbance (Hamilton & Snedaker, 1984).

Seedling collection is best done at low tide and must include collection of an intact plug of mud around the roots of about 30 cm depth and 15 cm diameter. This can be done using a shovel and a volunteer's hands in soft mud, transferring the seedling's root mass and soil to a surrounding bag or sacking to protect the root mass during transport. If the sediment is sandy, it is less cohesive and thus difficult to retain around the roots, while silt or mud is more cohesive and easier to keep as a protective root plug.

#### 5.1.4.5 Wild seedling collection and transplanting

As an alternative to propagule planting (Figure 52), existing seedlings can be dug out from areas where they are too dense and relocated to rehabilitation areas. The advantages of this method are that seedlings can be collected at any time of the year, and success rates are usually higher than with planting seeds. The disadvantages are that sources must be selected with care, and seedlings are more difficult to transport.

Mangrove seedlings for replanting can be collected from large, mature mangrove ecosystems where natural regeneration is occurring and which have a score of 1 in the Recruitment section of the vulnerability assessment (subsection 3.2.1). It is best to choose young seedlings because these have growth reserves remaining in the hypocotyl that will help their establishment after relocation. Youth is shown by there being few leaf scars on the stem below the lowest leaves (Duke & Pinzón, 1992). Seedlings should not be removed when they have a chance of reaching maturity where they are, and low-resilience areas, such as the seaward edge or creek edges, should be avoided. The best areas are where there are an abundance of seedlings under the shade of mature trees, with competition from other seedlings (Figure 63).



Photo: Brigid Morrison

**Figure 63.** *Rhizophora stylosa* seedlings in Fiji suitable for transplant because they are too dense, under shade and also young. Youth is shown by there being no or very few leaf scar rings under the lowest leaf pair.

### 5.1.4.6 Nursery raising of seedlings

Raising mangrove seedlings in nurseries from collected propagules can increase rates of survival and growth after planting, compared with the direct planting of propagules (Figure 52). This approach allows the seedling to develop a healthy root system before planting. Propagules without woody thickening are more prone to crab attack (Chan, 1996). Another benefit of raising seedlings in nurseries is that this will provide a year-round supply for rehabilitation activities.

Growing seedlings starts with planting propagules, preferably in a mixture of sand and mangrove mud. Poly bags are best used, about 30 cm depth and 15 cm diameter; these can easily be relocated and should have holes to allow drainage. Plastic pot containers with holes can also be used (Bohorquez, 1996; Figure



Photo: Joe Garrison

Figure 64. Young *Rhizophora* seedlings in a nursery.

64). Seedlings should be watered once or twice a day with dilute seawater mix. This suppresses fungal infections and acclimatizes the seedlings to saline conditions. Alternatively, location of the nursery within a low-energy intertidal area allows watering to occur naturally, and the mangrove seedlings are better acclimatized to the mangrove conditions where they are to be planted. An upper intertidal area is better than a lower and wetter area.

### 5.1.4.7 Planting seedlings

Planting can be done by digging a shallow hole that fits, taking any wrapping off and placing the seedling root mass in the hole. The mud level in the sacking bag must be the same level as the mud in the mangrove swamp. If the seedling is buried deeper, it will likely die (Ellison, 1998). Seedlings should be spaced in open areas at 1 m intervals (Agaloos 1994; Hong, 1994). The area should be protected from dogs, cattle and pigs, which can push over young seedlings while foraging.

### 5.1.4.8 Monitoring and ongoing management of replanted areas

After the establishment of a mangrove planting area, it is essential to monitor progress (Field, 1998; Gilman and Ellison, 2007; Sima, 2010) and to allow overall assessment of the replanting to guide future activities. This should include monitoring the growth of planted mangroves, assessing the mortality of seedlings and checking for human or other disturbance.

For replanting actions to be successful there must be ongoing management of weeds, grasses and climbers that may compete with the mangroves, particularly at landward sites and removal of debris that may move around at high tide and knock the seedlings over. The WWF pilots found that weeding and maintenance (Figure 65) is essential for successful mangrove replanting in sites close to the landward margin of mangroves (which is part of adaptation planning for inland migration).



Photo: Frank Sima

**Figure 65.** A village mangrove volunteer clearing invasive vine from *Bruguiera gymnorhiza* in a landward section of the Rufiji Delta, Tanzania.

## 5.2 Active adaptation options

Section 5.1 described a range of actions that reduce stressors to mangrove systems, thereby improving mangrove resilience. Section 5.2 describes actions that actively enhance the adaptive capacity of those mangrove systems to survive rising sea level.

### 5.2.1 Manage for accretion in mangroves

The habitat stability of mangroves depends on the maintenance of soil elevation relative to sea level, which, in the case of sea level rise, requires surface accretion. This allows mangroves to naturally adapt to rising sea level and can be facilitated by managers who understand the sedimentation processes and allow accretion to occur.

Mangrove conservation and restoration efforts must consider how to enable forests to keep pace with sea level rise (Huxham et al., 2010). Substrate elevation change is the net consequence of the site sediment budget (Figure 40). Major sources include input from

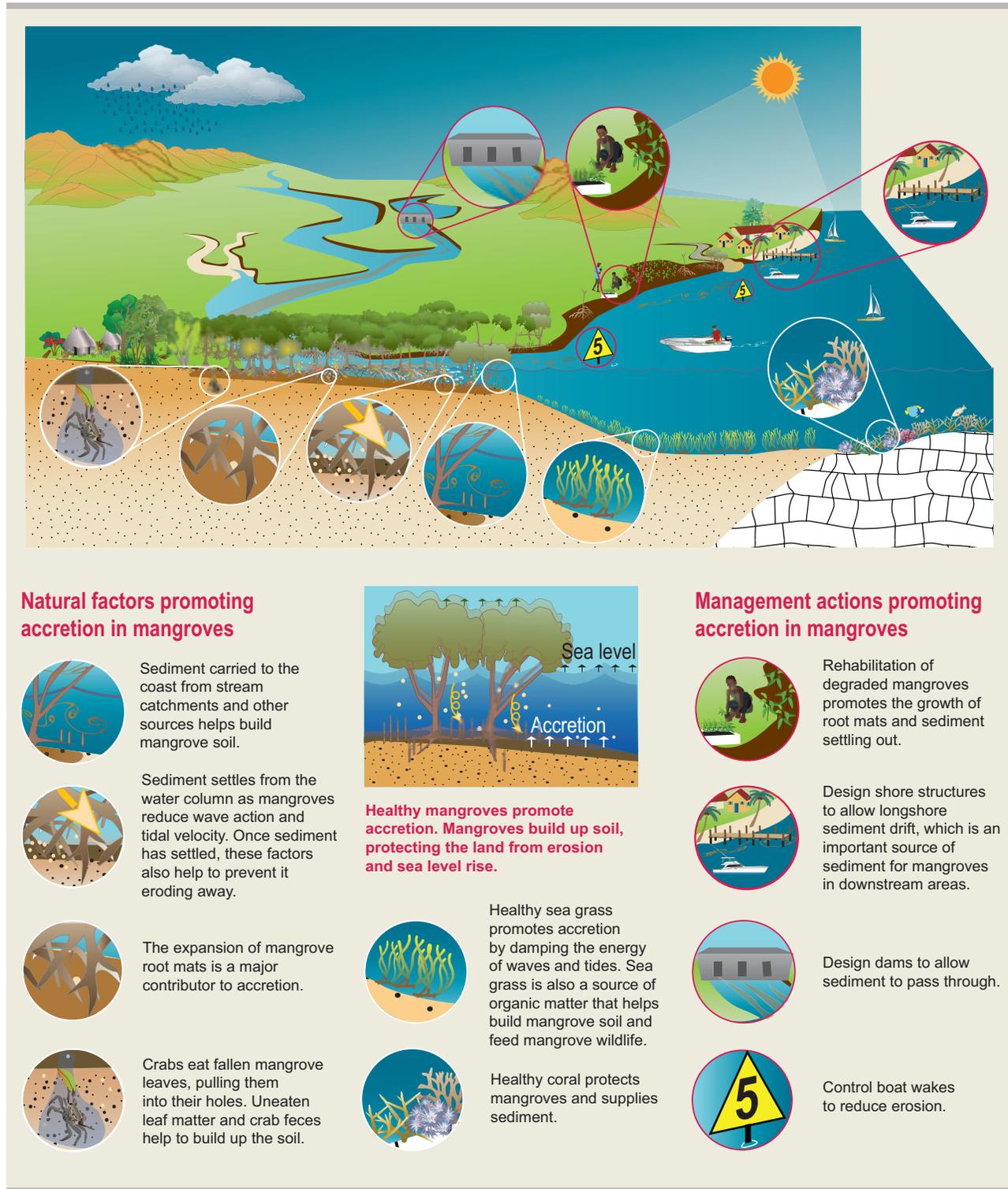
rivers in riverine settings, longshore transport, gains from offshore that occur mostly during high magnitude storm/tsunami events, and autochthonous input from mangrove productivity. Major losses include longshore transport down-coast, mangrove litter and sediment loss offshore and erosion. Erosion can be enhanced by higher-energy conditions such as boat wakes, which also tend to affect the seaward edge and creek margin mangroves, which are more vulnerable to sea level rise.

The sediment budget is a balance of volumes of sediment entering or leaving the mangrove environment, influencing whether the mangrove surface accretes or erodes. Accretion is influenced by *in situ* processes, such as decomposition of organic matter, compaction of the sediment column and root mat growth. A range of management actions can maintain and enhance mangrove sediment accretion (Figure 66).

Root mat growth has been found to be a major contributor to surface elevation gain and is especially important in mangroves that have no rivers and so have low inputs of mineral sediment, such as low island settings (Table 2). Rapid vertical development occurs when mangroves are more productive, but elevation losses occur where plant growth is low (McKee et al., 2007). Root mat growth has been shown to be higher under dense, healthy mangrove forests and lower under dwarf or scrub mangroves (McKee, 2011). Enhancement of the productivity of mangroves leads to marsh elevation gain (Langley et al., 2009). These studies indicate that improving the condition of mangroves also promotes accretion in those mangroves.

Dense seedlings promote sedimentation from root mat development, causing sediment surface elevation gain under densely replanted mangroves at both high and low tidal sites (Huxham et al., 2010). Seedling density also enhances accretion rates by providing friction to tidal water movement to promote sediment flocculation and settling (Huxham et al., 2010; Kumara et al., 2010). Actions to enhance root mat productivity include reduction of non-climate stressors (subsection 5.1) and replanting of degraded mangrove areas with dense seedlings (subsection 5.1.4), which will enhance root mat growth and so reduce vulnerability to rising sea level.

Dense, healthy mangroves promote sedimentation not only from root mat growth, but also from friction of



By Jan Tilden

Figure 66. Actions to enhance accretion in mangroves.

dense roots to water movement promoting sediment settlement from the water column (Furukawa & Wolanski, 1996; Furukawa et al., 1997). In densely vegetated mangroves, forest tidal velocities are reduced; and this friction on water movement, combined with flocculation of clays, contributes to substrate accretion (Furukawa & Wolanski, 1996; Furukawa et al., 1997). The density of mangrove vegetation further exerts a drag coefficient on tidal waters to protect the sediment from erosion (Mazda et al., 1995). *Rhizophora* prop roots assist in the settling of suspended sediment from estuarine waters (Krauss et al., 2003), and *Sonneratia* and *Avicennia* pneumatophores can promote sediment accretion (Young & Harvey, 1996; Krauss et al., 2003).

At mangrove seaward or creek margin edges where erosion is occurring, a network of sediment stakes that replicate *Avicennia* pneumatophores has been shown to increase sediment settlement (Young & Harvey, 1996) to raise the level up to where it can be replanted with mangroves.

Reduction in sediment supply at the coastline can result from increased human population at the coast and associated development, such as jetties (Appeaning Addo, 2011). Foreshore developments can reduce longshore drift of sediment, thereby reducing the supply of sediment into mangrove areas. These developments include coastal engineering structures, such as groins, that starve down-drift sections of sediment supply. Finally, dam construction on rivers reduces the volume of water and riverine sediment supply to the sea and coastal mangroves (Arthuron & Korateng, 2006), which can lead to a sediment supply deficit.

These activities all contribute to the increased vulnerability of mangrove areas to rising sea level, as resilience depends on sediment supply. Management actions to enhance sedimentation in mangroves therefore need to include coastal planners, infrastructure managers and river management agencies to build in design components that ensure continued sediment supply to the mangrove areas. Given the protection functions and other values of mangroves (Figure 2), these agencies and stakeholders will appreciate advice on how to maintain mangrove resilience.

In summary, the following actions promote mangrove sedimentation:

1. Reduction of non-climate stressors, such as human impacts, to improve health and condition of the existing mangrove forest
2. Rehabilitation of degraded mangrove areas, particularly sections that are eroding, as dense seedlings enhance accretion
3. Coastal zone planning to remove obstructions to sediment supply. This includes removal or redesign of coastal structures that interrupt longshore drift or enhance reflective wave action.
4. Prohibition of sediment removal or dredging from areas that are a source of sediment to mangrove areas
5. Reduction and control of boat wakes close to mangrove areas and margins. Boat wakes increase wave action and enhance creek bank erosion.
6. Influencing river dam design and operation to maintain fluvial sediment supply to the mangrove area

These management actions are illustrated in Figure 66.

Active enhancement of mangrove sediment accretion rates, such as by use of coastal structures, has been shown to be successful in mangrove restoration along an eroding coastline in Malaysia (Hashim et al., 2010; Kamali et al., 2010; Tamin et al., 2011). Another possibility is the beneficial use of dredge spoils, which could augment mangrove sediment elevation (Lewis, 1990) but which would need to avoid excessive or sudden sediment deposition that can kill mangroves (Ellison, 1998; Terrados et al., 1997). An accidental dredge spill onto an offshore tidal flat occurred in King Bay, Western Australia, and sediment transported into the mangroves by tides provided a 1 to 2 mm deposition (Semeniuk, 1994). WWF's adaptation pilots did not try either of these options, but it is an area for future research, particularly if the higher sea level rise projections prove to be correct.

## 5.2.2 Plan inland migration areas

Active planning for conditions under rising sea level includes inland zoning for future mangrove migration areas as part of multi-sectoral regional coastal planning that integrates mangroves into an overall adaptation strategy.

Mangrove area management and planning can accommodate for sea level rise using results from the VA components of relative sea level trend analysis (subsection 3.5) and elevation survey (subsection 3.4). Inland buffer zones that confine coastal development can be incorporated into land-use planning to provide an opportunity for habitats and wildlife to migrate inland.

In the first elevation survey case study (subsection 3.4.1) differential GPS survey results are given for low-lying areas inland of Rufiji Delta mangroves, showing sea level rise positions for increments of 10 cm above the current high tide. Global sea level rise is projected as 0.18 to 0.59 m by 2099 (IPCC, 2007b). Subsequent assessments consider this an underestimate and project that it could be 1 m or more (Vermeer & Rahmstorf, 2009; Grinstead et al., 2010; Jevrejeva et al., 2010). In planning for future sea level rise, it is therefore wise to consider increments of up to 1 m. Hence, as shown in Figures 24-25, mangroves can be expected to migrate by recruitment into those areas currently above high tide mark, which will also become less suitable for forestry or agriculture due to more regular saline inundation.

Planning for such future sea level rise should include the following considerations:

- elevation and gradient of land behind mangroves (subsection 3.4)
- sedimentation rates within mangroves and areas behind mangroves (subsection 3.6)
- background relative sea level trends of the area (subsection 3.5)
- barriers to migration, such as roads or railway tracks
- any development that may become problematic if inundated, such as rubbish dumps
- local communities that may need relocation

The involvement of local communities in planning for changing conditions is exemplified by the Tikina Wai case study in subsection 3.9.

If the tidal range of the mangrove area is low, such as <1 m, then it is best to plan to replant inland migration areas with mangrove species tolerant of deeper water, such as *Rhizophora*, but if the tidal range is 3 m or more, planting with higher-elevation species, such as *Bruguiera* or *Heritiera*, would give better results. This is because tidal ranges will be more totally relocated in microtidal areas than macrotidal areas (Figure 3). Subsection 5.1.4 can be used for replanting guidance.

Planned coastal retreat will allow mangroves to migrate and retain their natural functional processes and values (Figure 2). Such forward planning gives sufficient lead time to enable economically viable, socially acceptable and environmentally sound management measures (Gilman et al., 2008). Adoption of legal and planning tools, such as rolling easements, can help make eventual abandonment more acceptable (Titus, 1991). Construction codes can include plans for mangrove landward migration based on a desired lifetime for coastal development.

Such planning requires multi-sectoral collaboration, an enabling policy environment and adaptive institutions at local and national levels (and maybe international). This planning can be instigated through use of results from the vulnerability assessment process to point out needs to governmental and other stakeholders. Guidelines for larger-scale multi-sectoral regional coastal planning that integrates mangroves in an overall adaptation strategy are provided in guides such as that published by the U.S. Agency for International Development (2009).

## 5.3 Ongoing monitoring and evaluation

Given the uncertainties about future climate change and sea level rise, as exemplified by the ranges and error margins of the projected changes, and the uncertainty of how increased CO<sub>2</sub> and changes in rainfall and sea level will combine to affect mangrove ecosystems and people, ongoing monitoring could be the most important adaptive management activity of all. Standardized methods as used in subsections 3.2.2 and 3.2.3 will enable the separation of local influences

from global changes to provide a better understanding of mangrove responses to sea level rise and global climate change (CARICOMP, 2000; Ellison et al., 2012).

Management of mangroves is best guided by information about mangrove extent and condition. The VA components, such as forest assessment, described in this manual have provided a baseline against which future change can be monitored. Ongoing repeat surveys as outlined below will provide useful monitoring information on management success, needs and climate change impacts. Ongoing monitoring also allows evaluation of the success of adaptation options once they are implemented, providing data on how the systems (both mangroves and local communities) respond. Community involvement with ongoing monitoring encourages information on mangrove condition to directly inform local management decisions.

The following methods are the most useful for ongoing monitoring of climate change impacts:

- mangrove extent (subsection 3.3) and condition (subsection 3.2.1)
- permanent plots (subsection 3.2.2)
- sedimentation rates (subsection 3.6)
- relative sea level rise (subsection 3.5).

This manual has provided guidance on how to assess the vulnerability to climate change of a mangrove area, along with the local communities and adjacent ecosystems that most interact with it. As the area responds to climate change and other stressors, as new threats emerge and as adaptation actions are implemented, the situation will change. It is important to actively use the results from this vulnerability assessment and adaptation plan, to monitor and evaluate their success and to reassess and revise plans and strategies as new information emerges.



Photo: Rob Anders

## 6.0 Conclusions

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Climate change, particularly associated sea level rise, is a major threat to coastal mangrove areas. Even the best-case scenarios for mitigation indicate that some degree of climate change will be a reality for centuries to come. It is therefore essential that we develop ways to reduce the vulnerability and increase the resilience of mangroves to climate change, and to facilitate this through adaptation planning.

The approaches to vulnerability assessment of mangrove systems described in this manual are multidisciplinary and integrating biotic and abiotic factors. They include accurate and validated methods for determining ecological integrity and the extent and effect of human uses and impacts, and they provide a baseline of indicators against which to monitor future change. These are necessary approaches for giving communities and decision-makers ways to assess the ecological integrity of ecosystems under stress (Borja et al., 2008). Forest assessments, if monitored and updated periodically, will provide early warning systems for abrupt changes in environmental conditions. Adaptation and resilience-building require a suite of thoughtful, preventive actions, measures and investments that reduce the vulnerability of natural systems while addressing community, subnational and national development needs (Fiu et al., 2010).

A standardized methodology to suit different ecological contexts across geographically diverse scales is difficult, even with a range of tools and approaches. Thus, there needs to be a platform for sharing lessons systematically within a geographic region with similar ecosystems and then across regions. Some vulnerability assessments can be costly and lengthy and would benefit from endorsement at a national or subnational level. National stakeholders should inform and maintain the national reporting of issues related to mangroves and integrated coastal zone management, including those linked to international processes such as the United Nations Framework Convention on Climate Change (UNFCCC) negotiations.

A critical concluding lesson is that a vulnerability assessment should not be treated as a one-off exercise with an end point, within the context of a discrete study or even a suite of studies over a few months. An assessment as described in this manual is only a starting point that should yield important yet provisional indications of climate change vulnerability and resilience. Much of the data and results obtained will effectively form no more than a baseline. Designing and establishing a long-term ongoing monitoring program, as outlined in subsection 5.3, to continue to observe and assess the complex dynamics of climate change impacts should be an essential outcome of all mangrove vulnerability assessments.

A key output from the WWF project and its pilot activities in Cameroon, Tanzania and Fiji was to compile their learning in order to develop these generalized guidelines for effective mangrove vulnerability assessment and planning adaptation to climate change. The best way to expand this learning further is through strengthened opportunities for knowledge-sharing among projects and institutions with regard to climate change adaptation and related activities; as well as improved dissemination of information related to coastal climate change vulnerability and adaptation.

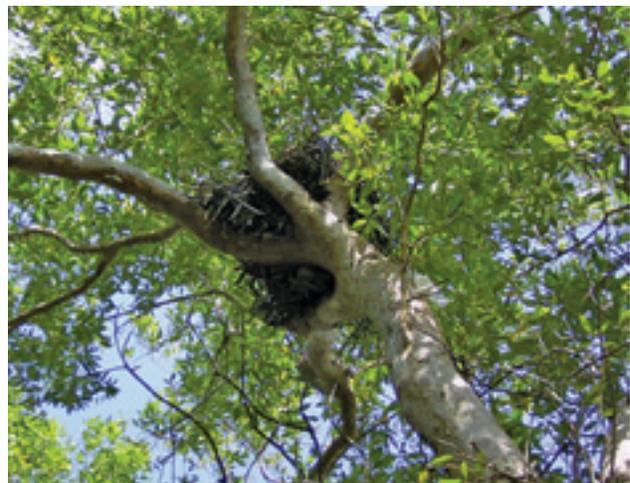


Photo: Joanna Ellison

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## 8.0 Glossary

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**Abscission collar** A region on the mangrove tree between the fruit and the propagule that becomes distinct when the propagule is mature and ready to be separated from the parent.

**Accretion** The process of vertical sediment accumulation that acts to increase surface elevation.

**Adaptation** An adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive, private and public, and autonomous and planned.

**Adaptive capacity** The potential or ability of an ecosystem or species to accommodate change with minimal disruption, either either through innate characteristics or human responses to reduce vulnerability.

**Allocthonous** An external source of sediment to the mangroves, particularly from rivers, so the sediment tends to be inorganic.

**Autochthonous** A sediment source that is produced from in situ mangrove production so the sediment tends to be primarily organic, resulting in peaty sediment.

**Base corrections** Corrections for coordinates and elevations according to real-time satellite information.

**Benthic** A benthic environment is at or near the bottom of a water body, and a benthic organism is one that lives there.

**Biodiversity** Used to describe the variety of all living organisms. Can also be applied at various scales such as genetic, species and ecosystem.

**Biomass** The total mass of mangrove trees expressed as mass per unit area.

**Calibration curve** Used to convert radiocarbon dates to real years through comparison of radiocarbon dates with independently dated carbon samples, such as using annual growth tree rings.

**Canopy** The upper vegetation strata created by forest foliage that structurally resembles a ceiling.

**Carbon sink** A reservoir that accumulates carbon and stores it on a long- or short-term basis. Mangrove systems act as carbon sinks in that forest growth removes carbon from the atmosphere where it is stored in biomass. Mangrove soils then act as a storage medium when the vegetation biodegrades and becomes soil organic matter.

**Climate change vulnerability** The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of exposure, sensitivity and adaptive capacity.

**Community structure** The relative numbers of different species that co-occur in the same habitat and interact through spatial or trophic relationships.

**Competition** Contest between individuals for limited resources, such as light and nutrients, to obtain a growth or reproductive advantage.

**Connectivity** The ability of functional groups to make necessary linkages that are spatially dependent within and among themselves (see Functional groups).

**Coral bleaching** The bleaching of coral as a result of polyps removing the color-providing zooxanthellae. This happens when corals experience environmental stress caused by water temperature fluctuation (mainly increases), increased solar irradiance, turbidity, herbicides, changed water chemistry or especially low tides.

**Delta** A depositional environment that can develop at the mouth of rivers where sediment is deposited from tidal discharge as water velocity slows to create distributaries and can create extensive intertidal flats.

**Deltaic subsidence** Subsidence of a river's coastal delta due to sediment loading on the tectonic plate, sediment compaction and fluid extraction, resulting in relative sea level rise.

**Disturbance** A physical or biological event that significantly alters the environmental controls of an ecosystem and that can be of short duration, like a tsunami, or longer, such as relative sea level change. Unsustainable human use of an ecosystem is also a disturbance.

**Downscaled climate model** A statistically derived climate or climate change model for local or regional application, using data compiled for robust but coarse-resolution global models.

**Ecosystem** A system of living organisms and their environment that functions in an interactive, interdependent manner. The fundamental components are plants that capture light energy to fix carbon as an energy source, and heterotrophs (animals) that consume and redistribute the energy fixed by plants.

**Exposure** An element of vulnerability in which extrinsic factors such as character, magnitude and rate of change may affect a species or system.

**Exposure factors** Potential external factors that might affect a species or system's vulnerability, requiring consideration of the cumulative effect of factors. In mangroves exposure factors include tidal range, rate of sea level rise and sediment supply.

**Flocculation** The process that contributes to mud cohesion by the physical aggregation of clay minerals by electrostatic forces on contact with salt water.

**Fringe** Mangroves along shorelines that face the open sea and are directly exposed to the action of both tidal water and sea waves.

**Functional groups** Groups of organisms that have followed similar evolutionary pathways and thus have morphological, physiological, behavioral, biochemical and environmental responses that are linked at a trophic level.

**Genera** A biological classification level between families and species that groups species by taxonomic similarity. This is the first word of a taxonomic species name.

**Geomorphic setting** The characteristics of the physical environment, including form and processes present, such as type of coastal landform and wave energy, under which a species or system is functioning and interacting.

**Georeferenced** An aerial or satellite image that has been located according to a map projection and coordinate system so that any position on it can be identified according to the map coordinate system.

**Global change drivers** Causes of environmental change, including climate change but also habitat fragmentation, reduced habitat quality and conversion.

**Green shield** A term for the structural role that mangroves play in protecting the coastline by absorbing energy from high winds and waves associated with storms or tsunamis.

**Ground-truthing** On-the-ground verification of features identified from spatial imagery such as aerial photographs or satellite imagery, especially in a GIS.

**Herbivory** The consumption of plants by animals.

**Hypocotyls** The leading stem or shoot of a germinating seedling below where the cotyledons (first two leaves) first appear. In most mangroves, this is a dormant stage to allow dispersal as a propagule.

**Intertidal zone** The area between the highest and lowest astronomical tide levels. The area can include higher tide levels increased by freshwater flooding, particularly within estuaries, or meteorological forcing.

**Isostatic adjustment** Movement of the Earth's crust in response to spatial change in ice, water and sediment loading and the subsequent force or relief that is exerted on the lithosphere.

**Lagoon** A protected, shallow-water environment that can develop within atolls or that is enclosed by coral, fringing or barrier reefs; cobble or sand spits; and barrier dunes. Lagoons may be partly or wholly separated from the sea.

**Landward margin** Where a few mangrove trees are present among freshwater or dry land vegetation.

**Late Holocene** The recent geologic time period that encompasses the latter part (last 7,000 years), of the epoch known as the Holocene that began around 18,000 years before the present day at the end of the last ice age.

**Leaf area index** A calculation for establishing green leaf area per unit of ground surface area. It is used to determine photosynthetic primary production, evapotranspiration and growth rates.

**LiDAR** Light Detection and Ranging. This airborne optical spatial technology sends multiple, rapid wavelengths of light to a target surface, which subsequently “bounce” back to the device thereby recording the surface elevation.

**Marine protected area** Marine areas that have been conserved for their natural environment values by some level of restriction of human activities and that can fall under the jurisdiction of various levels of authority.

**Mean sea level** The average of tidal water level heights determined from a long record and calculated from tide gauge records.

**Macrotidal** A tidal range of over four meters.

**Microtidal** A tidal range of less than two meters.

**Near–shore** An area that lies within the shoreline and the breaker zone.

**Offshore** An area beyond the breaker zone and extending out to the continental shelf.

**Phenology** The seasonal timing of fruiting and flowering, which is influenced by climate and is of significance for pollination.

**Plumule** The first shoot spikes at the top of the hypocotyl.

**Pneumatophores** The snorkel-like aerial roots of mangrove genera such as *Sonneratia* and *Avicennia*. They come vertically out of the ground from horizontal below-ground roots.

**Pollen analysis** The identification and relative abundance of pollen fossils preserved in the sedimentary record, used for reconstructing past environments such as mean sea level.

**Primary production** Plant biological productivity from photosynthesis, to produce organic material or biomass. The basis of ecosystem food webs.

**Propagule** Any part of a plant, such as a seed, hypocotyl, leaf or branch, that can be detached and grow into a new individual.

**Proxy sea level history** A sea level history indicating the timing and magnitude of past sea level change, usually documented from the calibration of modern ecological indicators of mean sea level with fossil evidence of these.

**Recruitment** Successful seedling growth that contributes quantitatively to a species population.

**Refuge** A location that provides suitable habitat where mangroves may be able to accommodate or adapt to climate change impacts.

**Relative abundance** The relative amount of organisms (usually a species) in a community, compared to others present.

**Relative sea level change** The sum of local, regional and global components of sea level change acting at a particular site. These components may include subsidence due to sediment compaction, regional uplift or tectonics or global sea level rise owing to ice melt or ocean thermal expansion.

**Replicates** A repeated set of scientific observations of one or more variables, often using sampling units such as quadrats or plots.

**Resilience** The ability of a system to absorb and recover from impacts or disturbance.

**Resistance** The ability of a system to withstand change and continue to function.

**River discharge** Water that flows from a river to the ocean such as into an estuary or delta.

**Riverine** An environment dominated by freshwater river hydrology and geomorphology.

**Rolling easements** A broad collection of approaches designed to restrict protective barriers to sea level rise and allow migration of coastal wetlands and shorelines or human access to them.

**Runoff water** Water derived mainly from rainfall that flows over the land surface due to gravity.

**Seaward edge** The farthest point in a seaward direction at which vegetation can establish and thrive.

**Sediment budget** The net balance of gains and losses of sediment from a landform such as a coastline. It is fundamental to whether the associated landform is building and accreting, eroding and retreating or in dynamic equilibrium.

**Sedimentation** The accumulation of inorganic particles after settlement down from the water above.

**Sedimentation rates** The rate of vertical sediment accumulation, usually measured in mm per year.

**Sensitivity** The innate characteristics of a species or system that influence its tolerance to changes in the biotic or abiotic environment.

**Species zone** An area that can be visually distinguished by the prevalence of a dominant species, or combination of species that co-dominate.

**Stakeholders** Individuals, groups, communities, organizations or government agencies that have an interest in a given natural resource.

**Stratigraphy** The study of sequences of rock or sediment from which past environments of deposition can be inferred and dated.

**Subsidence** Fall in elevation of the Earth's crust that can result from tectonic movement, adjustment to changes in ice or water loading, or sediment loading and compaction.

**Surge** A temporary rise in relative sea level caused by ocean water being pushed up to the shoreline by wind or wave energy and usually associated with storm and/or flood events.

**Survivorship** The number of individuals that survive until maturity, usually expressed as a relative percentage.

**Tidal range** The vertical difference between highest high tide and lowest low tide.

**Transect** A designated line or belt that is deployed through an area to be sampled, the dimensions of which are dependent on the needs of a study.

**Turbidity** Turbid water is that in which sediment is suspended in the water column. High turbidity will make water appear murky and can seriously affect water quality, such as reducing sunlight penetration to coral or sea grass.

**Vegetative production** Amount of live mangrove forest material generated from photosynthesis, measured in grams per square meter.

**Viviparous** In mangroves, the state of the hypocotyl already being germinated before leaving the parent tree, as opposed to the seed being the dispersal unit as in most other higher plants.

**Waypoint** A location that is recorded and stored in a GPS device to establish its coordinates and that can be downloaded into a GIS for mapping.

**Zone transition** An area that contains a mixture of species from adjacent zones where neither is dominant.



## 9.0 Acronyms and Abbreviations

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**AOGCM** Atmospheric and Oceanic Global Climate Model

**ASTER** Advanced Spaceborne Thermal Emission and Reflection Radiometer

**BA** Basal area

**BM** Benchmark

**BP** Before present (1950)

**CARICOMP** Caribbean Coastal Marine Productivity Program

**CARE** Cooperative for Assistance and Relief Everywhere

**CASI** Centre for Aerospace Information

**CRISTAL** Community-Based Risk Screen Tool – Adaptation and Livelihoods

**CVCA** Climate Vulnerability and Capacity Analysis tool

**DBH** Diameter at breast height

**dGPS** Differential Global Positioning System

**E** Elevation

**EDM** Electronic distance meter

**ERS** European Remote-Sensing Satellites

**FAO** Food and Agriculture Organisation

**GBH** Girth at breast height

**GCM** Global climate model

**GEF** Global Environment Facility

**GIS** Geographical information system

**GPS** Global positioning system

**H** Height

**ID** Identification

**IPCC** Intergovernmental Panel on Climate Change

**IUCN** International Union for Conservation of Nature

**LANDSAT ETM** Landsat enhanced thematic mapper

**LANDSAT MSS** Landsat multispectral scanner

**LANDSAT TM** Landsat thematic mapper

**LiDAR** Light Detection and Ranging

**MSL** Mean sea level

**PSMSL** Permanent Service for Mean Sea Level

**PVC** Polyvinyl chloride (a type of plastic)

**RSLR** Relative sea level rise

**RTK** Real time kinematic (receivers)

**S** Score

**SLC** Scan line corrector

**SLR** Sea level rise

**SRES** Special Report on Emissions Scenarios

**UHF** Ultra-high frequency

**UNEP** United Nations Environment Programme

**UNFCCC** United Nations Framework Convention on Climate Change

**US** United States of America

**USAID** U.S. Agency for International Development

**USGS** United States Geological Survey

**VA** Vulnerability assessment

**WWF** World Wildlife Fund

# Appendix: Data Sheets

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## Data sheet for mangrove rapid assessment

Date : \_\_\_\_\_ Time: \_\_\_\_\_ Site name: \_\_\_\_\_

Data collectors: \_\_\_\_\_ Transect number: \_\_\_\_\_

Description of start point (seaward or landward?) \_\_\_\_\_

Transect start, Latitude: \_\_\_\_\_ Longitude: \_\_\_\_\_

Description \_\_\_\_\_

Compass heading: \_\_\_\_\_

Zone	Species present	Width (m)	Degree of impact	Impact type (see Table 6, p. 16)	Height of water mark on trees (cm)
1					
2					
3					
4					
5					

Transect end, Latitude: \_\_\_\_\_ Longitude: \_\_\_\_\_

Notes on seaward edge: (i.e., eroding, accreting with seedlings?)

Remarks: \_\_\_\_\_





## Data sheet for mangrove permanent plot measurement –2

Sketch map of mangrove plot showing approximate location of each tagged tree.

A large, empty rectangular box with a thin black border, intended for a hand-drawn sketch map of a mangrove plot. The box is currently blank, providing space for the user to draw the layout of the plot and the locations of tagged trees.

Add an arrow indicating the direction of north, a scale and any features like fallen trees.





## Data sheet for sedimentation stakes

Date : \_\_\_\_\_ Time: \_\_\_\_\_ Site name: \_\_\_\_\_

Data collectors: \_\_\_\_\_

Permanent plot location: \_\_\_\_\_

Direction facing during measurement: \_\_\_\_\_

Stake	Height (mm)
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	





