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Preface

Message from the Kenya Marine and Fisheries Institute:

Kenya Marine and Fisheries Research Institute (KMFRI) is delighted to host the 2013 International Mangrove Training Course in the Western Indian Ocean region (WIO). Mangroves in the WIO countries constitute about 5.0% of the current global mangrove coverage. A number of these mangrove forests are shared by several countries in the region. Besides the common uses for firewood, charcoal and building materials, herbal medicine and traditional lime making are common practices in coastal communities throughout the WIO region. Mangroves are also critical for food security in WIO; as they serve as habitats and breeding grounds for marine fisheries. Their value as carbon sinks for climate change mitigation has recently been more appreciated as mangroves sequester 3 - 5 times more carbon per unit area than any forested ecosystem.

Pressures on mangroves throughout the WIO countries are similar and are mostly human-induced. The area of mangroves in the region that has been lost over the last century is estimated to exceed 50% of the current area. Direct causes of mangrove degradation include over-exploitation of wood products, conversion of mangrove land to other land uses (particularly aquaculture and agriculture) and pollution effects. Other causes include reduction in freshwater flow through damming of major rivers, increased sedimentation, and coastal development.

Major consequences associated with mangrove degradation in the entire WIO region include shortages of wood products, decline in fisheries, and increased coastal erosion. These ultimately lead to loss of livelihood and increased poverty among the coastal population and are worsened by lack of mangrove management plans in many WIO countries.

For these reasons we are delighted that our sponsors; particularly the Western Indian Ocean Marine Science Association (WIOMSA) and the United Nations University-Institute for Water, Environment and Health (UNU-INWEH) have generously supported the 2013 International Training Course on Mangrove Ecosystems. This is the first time the course is being organized in our region. For ten days, nominated participants from WIO countries will interact with an international team of mangrove experts in a setting that presents the most studied mangroves in Africa. Discussion topics will range from; mangrove taxonomy, biodiversity and ecosystem functions in mangroves, methods of studying mangrove forest structure and functions, climate change impacts/vulnerability assessments, and tools for managing mangroves among others. Topical issues on mangroves of the WIO will also be discussed. Both plenary and group mode of training will be pursued during the course period. At the end of the course an evaluation exercise will be conducted with the goal of improving future training courses.
Message from the United Nations University – Institute for Water, Environment and Health (UNU-INWEH):

UNU-INWEH is delighted to be part of this First Regional Training Course on Mangrove Ecosystems for the WIO region. This course will be the first training activity officially implemented under the WIO Mangrove Network (WMN) in partnership with, Coastal Oceans Research and Development in the Indian Ocean (CORDIO), the University of Nairobi and the Kenya Marine and Fisheries Research Institute (KFMRI), in the hopes that it will become an annual course to be held in this region.

We are especially excited to work with these dedicated national and regional partners, who have been extremely supportive and effective in getting this course off the ground. We are very grateful to WIOMSA, the UNEP Nairobi Convention and WWF East Africa for their support.

Building and enhancing the capacity to manage mangrove ecosystems effectively is a key goal of UNU-INWEH. It aims to foster sound decision-making, especially in developing countries, through scientific research, and human and institutional capacity-building in the field of coastal management. Our activities focus on a range of issues in tropical coastal systems, including mangroves, particularly in developing countries, while maintaining an integrated and holistic approach towards coastal management.

UNU-INWEH has played a significant role in mangrove conservation and restoration through promotion of education, research and awareness-raising. One of the organization’s most significant contributions has been to undertake research and capacity development for mangrove conservation and restoration. Towards these ends, for over a decade, UNU-INWEH has conducted a training course in India to build the capacity of professionals and institutions in developing countries of the Asia-Pacific region to undertake monitoring, research and conservation of mangrove ecosystems. The course has trained young professionals in scientific methodologies and management practices for mangroves and has facilitated the development of a network of researchers, educators and managers within the region.

Over the years, mangrove experts and course participants have favorably evaluated this course, and have lauded the initiative and its regional impact. In extending this course to East Africa and connecting with organizations that are regional leaders in mangrove conservation, UNU-INWEH hopes to replicate and expand the success already achieved.

Message from the University of Nairobi (UoN):

The University of Nairobi is delighted to partner with the Kenya Marine and Fisheries Research Institute (KMFRI) and the United Nations University - Institute for Water, Environment and Health (UNU-INWEH) in organizing the First Regional Training Course on Mangrove Ecosystems for the WIO region. The UoN vision and mission is to be a world-class university committed to scholarly excellence and to provide
quality university education and training and to embody the aspirations of the Kenyan people and the
global community through creation, preservation, integration, transmission and utilization of
knowledge.

Mangroves are important globally due to the goods and services derived from them. Of particular
interest is their role in shore line protection and climate change mitigation through carbon
sequestration. Climate change is impacting countries worldwide, and in particular, developing countries.
This underscores the need for mangrove protection, conservation and rehabilitation of degraded
mangrove ecosystems which cannot happen without expertise. To raise awareness and counter the
effects of climate change there is need to continuously train experts to address these challenges. The
objectives of this training course will go a long way in giving the necessary training, skills and hands on
experience to the participants who will, in return, be active in mangrove research in their respective
countries within the WIO region. The UoN is also delighted that their academic staff and post graduate
students will be participating in this training which is in line with the institutions core values of training
and research. The UoN College of Biological and Physical Sciences applauds the participation of the
Master of Science students in Biology of Conservation and Economics in this course. The course will
equip the students with the relevant skills and tools to enable them undertake their research projects in
coastal ecosystems. The UoN looks forward to this training course being an annual event in this region.

The UoN embraces the spirit of collaboration, networking and linkages with local and international
institutions in innovation, implementation and knowledge dissemination in issues of global concern. It is
therefore delighted to be associated with WIO Mangrove Network (WMN), Coastal Oceans Research and
Development in the Indian Ocean (CORDIO) and the earlier mentioned institutions in mounting this
relevant training course. The contribution of WIOMSA, the UNEP Nairobi Convention and WWF East
Africa is also highly appreciated and UoN looks forward to future collaborations.

The UoN acknowledges that this course, the first of its kind in Kenya and the region and hosted by the
University’s Moana Research Field Station in Diani (South Coast) will move mangrove research in Kenya
and the WIO region to the next level. The University wishes the group an enjoyable, productive and
interactive stay in Moana and looks forward to hosting many more training courses in the future.

**Message from CORDIO East Africa:**
CORDIO East Africa is delighted to partner with the United Nations University - Institute for Water,
Environment and Health, the Kenya Marine and Fisheries Research Institute and the University of
Nairobi in the first training course on mangroves to be held in the Western Indian Ocean (WIO) region.
CORDIO’s current Strategic Programme embraces research for management of all interrelated coastal
ecosystems. Mangrove forests are an integral part of the WIO’s coastal marine environment. Mangroves
play a significant role in the productivity of nearshore and offshore marine environments and provide a
critical ecosystem service to the people living along the coasts of the WIO, through, for example,
protection from storms, wood products and a multitude of fisheries. It is our hope that this course will
enhance the technical capacity of mangrove researchers and managers in the region and further build a
thriving community of mangrove practitioners to improve the protection and management of the substantial mangrove forests in the WIO.
Acknowledgments

This International Training Course on Mangrove Ecosystems premiers in the region after 12 such successful past trainings held in India, thus becoming the first training course to be held in the Western Indian Ocean Region. This training is very important owing to the fact that mangroves are a critical resource supporting millions of livelihoods in the region, but have often been ignored and thus received less attention in management compared to other resources.

The training was made possible through generous support from the Western Indian Ocean Marine Science Association (WIOMSA), WWF – CEANI (Coastal East Africa Initiative), UNEP Nairobi Convention (under which the WIO Mangrove Network hosting this course is anchored) and the University of Nairobi for providing accommodation and training facilities. Additional support has also come from partners involved in organizing this course namely: Kenya Marine and Fisheries Research Institute (KMFRI), the United Nations University Institute for Water, Environment and Health (UNU-INWEH) and the Coastal Oceans Research and Development - Indian Ocean (CORDIO). All the resource persons who dedicated time in the preparation of this training manual and delivery of the course through lectures and fieldwork are also much appreciated.
Rationale for this course

Mangroves are extraordinary ecosystems, located at the interface of land and sea, that offer a considerable array of ecosystem goods and services. They are vital for food security and protection of coastal communities; they provide a wide diversity of forest products, nurseries for aquatic species, fishing grounds, carbon sequestration, and crucial natural coastal defences that mitigate the impact of erosion and storm action. Despite their value, nearly all mangrove nations have experienced net losses in cover in recent decades, and remaining mangrove habitats are seldom pristine. About one fifth are thought to have been lost globally since 1980 due to a suite of anthropogenic threats.

The Western Indian Ocean (WIO) region is an important mangrove region that is geographically distinct and isolated from both South and South-East Asia by the Indian Ocean, and the arid and largely un-vegetated coasts of the Middle East (Spalding et al. 2010). Mangroves exist along the entire coastline of Madagascar, and are patchily distributed along its offshore small island archipelagos. The coasts of the Comoros and Mauritius have limited coverage, with more widespread coverage on the Seychelles. Extensive and diverse formations are also found in the slightly wetter coastlines that extend along Kenya, Tanzania and north and central Mozambique. The Mgazana Estuary coastline in South Africa marks the southern limit for mangroves in Africa (Spalding et al., 2010).

Mangrove forests provide an array of ecosystem goods and services which support the livelihoods of millions of people in the Western Indian Ocean region through fisheries production, provision of wood products, coastal protection, biodiversity conservation and cultural values. In the context of climate change, the global role of mangroves as carbon sinks has become more appreciated as they sequester about five times more carbon per unit area than any productive forest ecosystem. The protective roles of healthy mangroves (erosion reduction, wave attenuation, sediment accretion, storm wave abatement) will be increasingly needed to protect shorelines against both rising sea levels and the increase in frequency and strength of extreme weather events. However, the decline of these spatially limited ecosystems due to multiple global and local pressures is increasing, thus rapidly altering the composition, structure and function of these ecosystems, and their capacity to provide ecosystem services essential for the livelihoods of people in the region. Compounding factors aggravating
mangrove degradation include overexploitation, land-use change, pollution and more recently, climate change.

Mangroves have suffered fewer losses in the WIO region compared to others, with only an 8% decline from 1980 to 2005 (FAO 2007). The impact of human activities on ecosystems in this region varies, but the local population is growing rapidly, placing increasing pressure on mangrove resources (Spalding et al. 2010). Threats include: over-harvesting, development, and the reduction of freshwater flow into estuaries (causing mangroves to flood). Mangrove utilization is heavy in Kenya and Madagascar, where they have been converted to rice paddies, salt pans and shrimp ponds. Also, inappropriate agricultural practices such as the cultivation of steep areas and contour furrows have led to catchment degradation, resulting in increased sedimentation. Mangroves here will also be subject to climate change effects.

Protection afforded to mangroves in the region varies, but is generally good. In both Kenya and Tanzania, mangroves have had some protection provided by general legislation dating back to the early 19th century, and there have also been some small-scale restoration efforts with quite large areas having been incorporated within protected area networks. Some obstacles that prevent complete mangrove protection include: the sectorial approach of management, lack of community input, poverty of indigenous coastal communities, and a lack of awareness amongst decision makers about the true value of mangroves (Spalding et al. 2010).

Over the past decade there has been a surge in mangrove ecosystem research, unveiling their ecological and economic importance to this region (Kairo et al. 2001, Kairo 2003, Kairo and Lang'at 2008). However, a major shortcoming is that there is no clear regional overview or baseline data available from which environmental impact assessments and management plans can be developed. Furthermore, available information is often not disseminated (Taylor et al. 2003). There is a real need for basic knowledge on many aspects of mangrove ecosystems; specifically in the methodologies and techniques of natural and artificial regeneration, faunal interactions, mangrove fisheries, hydrology, and growth and development (MFF 2011). Although in the recent past there have been some training and research activities (e.g., The Management of Mangroves using Payment for Ecosystem Services training course conducted by Earthwatch in 2011 and held in Gazi Bay with the Kenya Marine and Fisheries Research Institute), none have focused on basic biology and ecology, or practical methodologies for assessment, monitoring, restoration and management. Understanding these basic attributes is crucial to understanding the true complexity, importance and value of these ecosystems, and would create a better understanding of how human activities are affecting mangrove ecosystems. This would allow for more efficient and sustainable management regimes to be developed.

The establishment of this course is particularly timely since capacity building has been identified by WMN as a major need within the region. Additionally, the location of the course in Gazi Bay is especially suitable since mangroves in the area form broad and diverse forests which are heavily relied upon by local people, are the basis for ecotourism activities, form part of an interconnected coastal ecosystem
that includes seagrasses and coral reefs, and have been well-studied. Therefore, this location affords an excellent opportunity for students to observe and engage with the many issues pertinent to mangrove ecology and management which they will learn about in lessons and group discussions.
Objective of this training course:

1. To reinforce and increase the capacity of young professionals, academics, park rangers, managers and institutions in the WIO region to undertake characterization, monitoring, risk assessment, management and restoration of critical mangrove ecosystems;

2. To increase the awareness of the ecological roles, economic importance, and cultural significance of mangrove ecosystems;

3. To promote and encourage sharing of knowledge and experiences.

Purpose of this manual:

This manual is a reference document for students. It intends to provide relevant information on the topics discussed and should be used by the trainee for review after the close of the training course. It also allows the trainee to concentrate on and partake in the training during the training sessions instead of taking detailed notes. Finally, it can serve as a reference document for the trainee in their work place and future endeavours.
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1.0 Introduction to Mangrove Ecosystems

1.1 Occurrence, Distribution and Diversity of Mangroves – Global Overview

**Background**

Mangroves are trees or large shrubs, including ferns and a palm, which grow in or adjacent to the intertidal zone. The term “mangrove” describes both the plants and the ecosystems they form. To describe the entire mangrove community, both living and non-living components, the following terms can be used: mangrove forest, mangrove swamp, mangal, marine tidal forest and coastal wetland.

These plants are found at tropical and sub-tropical latitudes, primarily along sheltered shorelines where freshwater (rainfall or river flow) dilutes the ocean, such as bays, estuaries, lagoons, backwaters, and rivers (up to the point where water remains saline). In these settings, mangroves inhabit the boundary of terrestrial, marine and freshwater ecosystems. The environment between these systems is harsh; being characterized by shifting sediments, regular tidal inundation, as well as variable and often high salinities (Kathiresan and Bingham 2001). Consequently, mangrove plants have unique adaptations which have allowed them to thrive and become the architects of remarkable forest ecosystems. They have adapted to life in wet soils, saline habitats, and periodic tidal submergence. These forests are structurally simple compared to rainforests, often lacking an understory of ferns and scrubs (Alongi 2002). They are also unusual among tropical forest ecosystems because they naturally have low plant diversity and high population density. This is a consequence of the physiological restrictions of living in the intertidal zone (Tomlinson 1986). Despite their structural simplicity, the mangrove is home to a remarkable array of animal species, many of which are found in no other habitat.

**Distribution**

Mangroves show considerable variation in their global density, distribution and coverage. They grow predominantly at tropical latitudes, but also occur in the subtropics, roughly between 30°N and 30°S. Within their latitudinal limits, mangrove distribution is largely influenced by temperature and moisture. Ideal conditions for growth include high humidity combined with freshwater input that provides silt and nutrients.
The tropical predominance of mangroves is well known, and while mangroves are widespread within these latitudinal limits, they show considerable variation in total areal coverage. Mangroves thrive in areas where pure seawater is diluted – by high regular rainfall, groundwater flows and rivers. Mangroves are most abundant along the wetter coastlines of South and Central America, West and Central Africa, and in a broad expanse starting from northeast India, through Southeast Asia and into north Australia (Spalding et al. 2010). Some mangrove forests stretch inland for tens of kilometres. A great example of this is the Sundarbans mangrove forests found along the borders of India and Bangladesh. Extensive mangrove forests can also be seen in the estuaries of large rivers flowing over shallower continental shelves, e.g., The Ganges in Bangladesh, Fly River in Papua New Guinea, and the Mekong Delta in Vietnam (Feller and Sitnik 1996). The Amazon and Congo, the two largest rivers in the world, do not have extensive stands of mangroves primarily because of the huge outflow of freshwater (Feller and Sitnik 1996). In more arid regions such as the Middle East, much of Australia, and East Africa, mangroves tend to occur in discontinuous sparse clusters and formations (Spalding et al. 2010).

**Global Patterns**

Mangroves can be divided into two distinct geographical realms based on their floral assemblages:

1) **Indo-West Pacific (IWP)/Old World Mangroves** - located in the eastern hemisphere. They range from east Africa, through Indo-Malaysia, and into Australasia. Mangroves are thought to have evolved in this area, thus the term ‘Old World’.

2) **Atlantic East Pacific (AEP) Mangroves/New World Mangroves** - located in the western hemisphere. Their range includes the Americas, and West and Central Africa.

The eastern hemisphere has 62 unique species and recognized hybrids (i.e., *Osbornia* and *Camptostemon*), while the Western hemisphere has 12 unique species and hybrids (i.e., *Pelliciera*, *Camptostemon* and *Osbornia*).
Conocarpus, and Laguncularia) (Kathiresan 2006, Spalding et al. 2010). There is almost no overlap in species between these two areas with the exception of one fern, Acrostichum aureum.

The fern Acrostichum aureum is found in both the Indo-West Pacific and Atlantic East Pacific regions. (Source: Spalding et al. 2010)

This biogeographical division is also reflected in the shallow marine taxa; corals, reef fish, and seagrasses. The disparity between species numbers (Old World having over 5 times more unique species) is part of the argument supporting the theory that the Old World is the origin of mangrove evolution. However, the disparity is not reflected in the extent of available habitats, since Old World mangroves have 57% of global mangrove area and the New World has 43% - roughly similar proportions (Spalding et al. 2010).

The two mangrove realms can be further subdivided into seven subregions: West America; East America; West and Central Africa; East Africa; Indo-Andaman; Southeast Asia; and Australasia.

Generally speaking, the majority of mangrove species have fairly extensive ranges. For example, the grey mangrove Avicennia marina extends from South Africa to the northern Red Sea and eastwards across the Pacific Islands. The red mangrove, Rhizophora mangle is similarly widespread, all over South America, Western Africa, Mexico, and Florida. In contrast, there are few species with highly restricted ranges, for instance Avicennia integra, which is limited to a distinct region in Northern Australia having only 1000 km² of mangrove habitat (Spalding et al. 2010).

Different mangrove species have remarkably different ranges: e.g. Heritiera fomes. (Source: Spalding et al. 2010)
Different mangrove species have remarkably different ranges: e.g. *Avicennia marina*.
(Source: Spalding et al. 2010)

**Diversity**

Some debate surrounds the number of total mangrove species, but the most recent global assessment considers 73 species and hybrids as true mangroves (Spalding et al. 2010). When compared to other forest types, mangrove diversity is considerably low. For example, the rainforests of the Malay Peninsula alone have about 8000 floral species of vascular plants which includes some 2500 tree species (ITTO/ISME 1993). The highest biodiversity is found in south and Southeast Asia, but there are also minor diversity centres in the West Indian Ocean and south Central America.

There is considerable inter and intraspecific variation among mangrove species. For example, physiological differences have been recorded between West African and Western Atlantic populations of *Avicennia germinans* (Saenger and Bellan 1995). This variation may be the result of genetic differences in certain traits, or from phenotypic responses to local environments. For instance, in Mexico, the mean leaf area of *Rhizophora mangle* is positively correlated with precipitation and negatively correlated with latitude (Rico-Gray and Palacios-Rios 1996). This climatic response may allow trees to maximize their photosynthetic abilities (Rico-Gray and Palacios-Rios 1996). Moreover, leaf area indices can be used to differentiate the *Rhizophora mangle* from basin and dwarf forest types in southeast Florida, United States (Araujo et al. 1997). Mangrove species can be discerned through visual inspection of physical characteristics; leaf structure, bark, twigs, aerial roots, flowers, and fruits/propagules, and growth structure (Feller and Sitnik 1996).
The diversity of mangrove species worldwide.
(Source: Spalding et al. 2010)
1.1.1 Occurrence, Distribution and Diversity of Mangroves in the WIO Region

Mangroves in Kenya
Mangroves are found along much of Kenya’s coastline, both in narrow fringing formations and in creeks and estuaries of major rivers. Despite semi-arid conditions, the most extensive mangroves are found in the north along the complex of creeks and embayments of the Lamu Archipelago and adjacent mainland (Spalding et al. 2010), and there are also important mangrove forests in the Tana River Delta. Smaller mangrove areas are found on Kenya’s only other perennial river, the Galana (or Sabaki), while Gazi Bay in the south has a broad and diverse mangrove fringe in a deep embayment with associated seagrasses and coral reefs. Some tourism has arisen around the Kenyan mangroves - like the 500m boardwalk in Gazi Bay which brings valuable income to the local community. Still, the most important use of mangroves is in the production of timber. Local timber consumption has continued to rise, most notably
Mangroves in Tanzania

Mangroves fragment most of the coastline which stretches to about 1,424 km long (including the coastline of the major islands and islets). Areas where large covers of mangroves are found coincide with riverine formations, sheltered bays and creeks. In mainland Tanzania, the largest continuous mangrove areas are located along the coasts of Mkinga and Tanga districts and Pangani estuary in the north; Wami and Ruvu estuaries and Rufiji delta in the central part; and Kilwa, Lindi and Mnazi Bay and Ruvuma estuary in the south. Mangroves are also well represented around Mafia, Unguja and Pemba Islands. In total they cover about 135,500 ha, albeit this estimate has considerable uncertainty. The Rufiji delta alone accounts for about 50% of the total mangrove area.

All mangrove forests in Tanzania are legally gazetted forest reserves since the colonial era (Holmes 1995, Sunseri 2005). However, this has generally not prevented their use by coastal communities as there is a tacit recognition that local villagers have traditional rights to use mangrove forests in a sustainable manner. Mangroves are harvested by coastal communities as a local material for construction and wood fuel (Semesi 1998, Wagner 2005). Estuarine mangroves are a prominent habitat for prawn fishery (McNally et al. 2011). Mangroves are also used for bee-keeping. There are a number of ecotourism initiatives carried out around mangrove areas such as the mangrove boardwalk in Jozani-Chwaka Bay National Park and the mangroves island bird sanctuary at Ukongoroni in Zanzibar are popular tourist destinations. Despite the value of these activities, major threats to mangroves are mainly use-related. Conversion of mangrove areas for other uses is a key driving force behind mangrove degradation. Mangrove forests are cleared to provide space for agriculture, aquaculture, solar salt production, urbanization and coastal development. Mangrove ecosystems located near urban centers like Dar es Salaam, Tanga and Zanzibar also suffer from various types of pollution including municipal sewage, garbage and oil spills. Although unlicensed commercial logging is not permitted, illegal harvesting has been going on all along. Restoration efforts are not well conceived as they are largely localized and uncoordinated with little practice knowledge of the prerequisites which has caused a number of failures.

Mangroves in Madagascar

In Madagascar, all large rivers and estuaries are situated in the north and west, supporting nearly 98% of Madagascar’s mangroves over a 303,814 ha area. A total of eight species of mangroves have been recorded (Radhik 2006, Roger and Andrianasolo 2003). The East coast has only a few stands covering about 5,000 ha (DGEF 2000). Most mangrove stands in the west coast cover areas of more than 500 ha, and areas like Betsiboka, Mahajamba, Mahavavy (Baie d’Ambaro), Mangoky, Ranobe (Besalampy) and Tsiribihina have mangrove covered areas of over 20,000 ha (Taylor et al. 2003). In the northern most side of the Island in the Antsohihy/Analalava area, there is extensive cover of mangroves. The southern mangroves extending up to around Cap St André, one finds large mangrove blocks well supplied by freshwater discharge from big rivers. In the south-west part of the Island, from around the Mangoky
River to the south end of the Island is a region that is characterized by low precipitation and low freshwater runoff, therefore one finds very few and scattered mangrove stands.

**Mangroves in Mozambique**

Mozambique’s nine species of mangrove trees are found along the 2,700 km coast, covering an area of 290,900 ha (Fatoyinbo et al. 2008). Mozambique has many trans-boundary rivers draining into the Indian Ocean thus making the mangroves highly productive. The largest blocks of mangroves are found within central Mozambique, and in deltas and large rivers estuaries (Barbosa et al. 2001), such as in Beira and the Save Rivers where mangroves cover extends up to 50 km inland. The southern coast of the country is characteristically sand-dune coastline, and mangroves are scanty, but well established stands occur on the estuaries of rivers such as Save, Incomati, and Maputo rivers as well as around larger bays such as Inhamabe and Maputo bay. *Avicennia marina* is the most widespread species, and colonises both inner and outer margins of the forests, however towards upper latitudes some inner parts are dominated by *Sonnerati alba* and *Rhizophora mucronata*, adapted to tolerate small variation in salinity. The northern coast is predominantly coraline, with coral reefs typically bordering the clear water subtidal areas of these locations. Mangroves are common and grow in the estuaries of the rivers, embayments and some areas protected from direct ocean currents. Extensive mangrove areas occur in the Quirimbas archipelago and several embayments near the archipelago (viz Palma, Ulombi, Mocimboa, Quiretajo). Other important mangrove areas are Pemba town bay with 33,600 ha (Ferreira et al. 2009) and the coastline of Nampula. Approximately 50% of Mozambique’s mangroves are located at the Zambezi delta (covering almost a 180 km of the coastline), which also represents the single-largest area of mangrove forests in Africa.

**Mangroves of South Africa**

In South Africa mangrove forests cover less than 1% of the area and are classified as the rarest and smallest forest type in the country. Limited to the eastern portion of the 3 000 km coastline, they are distributed from the border of Mozambique at Kosi Bay in KwaZulu-Natal to Nahoon Estuary in East London (Eastern Cape), which itself is an anomaly as mangroves were planted in the latter in 1969. Although mangroves cover a small area in comparison to coastal countries north of the border they make an important contribution to ecosystem functioning and services. There are seven mangrove species in South Africa and the dominant species is *Avicennia marina* (Forsk.Vierh.) also known as the white mangrove in some parts of the world. Mangroves are harvested for building material, firewood or charcoal, small scale honey production, fish traps and livestock grazing.

**Other WIO Mangrove countries**

Other WIO mangrove countries include Mauritius, Comoros, Seychelles and Somalia. Two species of mangroves have been reported from Mauritius namely *Rhizophora mucronata* Lam. and *Bruguiera gymnorrhiza* (L.) Lam. (Sauer 1962). *Rhizophora mucronata* is the most dominant species of the two (Fagoonee, 1990). In the past, mangroves have been reported to be widespread along the coastal region of Mauritius. The area under mangroves cited in the literature is 20 km² (Spalding 2010, Appadoo 2003,
It is reported that mangroves were destroyed during the British occupation in an attempt to control the malaria epidemic in the 19th century. Nearly 4000 people died following the epidemic of 1866 (Shaen and McIntosh 2004). For the Seychelles, there are mangrove stands on Curieuse at the end of Bay Laraie, in the lagoon of Aldabra and at 12 sites around Mahé. The largest stand on Mahé, around 20ha, is close to Port Glaud/Port Launay in an area called La Plaine Marsh. Other large areas include those at Anse Intendance, 13ha, and Anse à la Mouche, 10ha. There are mangroves at Baie Ste Anne, Anse Volbet, Anse Possession and Grand Anse on Praslin and in Anse Severe on La Digue. However, the largest overall mangrove areas are found on Aldabra, Cosmoledo and Astove. Of the seven mangrove species found on the 115 islands that make up the Seychelles *Avicennia marina* is the most abundant (Taylor et al. 2003). Mangroves in Somalia are found in three tidal estuaries between Saada Din Island and Saba Wanak in the extreme south of the country. The Caanoole Estuary and the Bushbush Estuary, which are tidal for approximately 30km inland, have narrow, 20m, mangrove fringes. Bushbush Game Reserve, Somalia’s only marine protected area with mangroves. Northern areas of Somalia are subtropical and thickets of low, scattered mangroves, usually *Avicennia marina*, exist. However, an upwelling of cold water inhibits abundant mangrove development. Mangroves have also formed in the low wave energy, intertidal zones of channels along the Kisimayo coast. The current status of all these mangrove areas is unknown.
1.2 Current Status and Threats to Mangroves - Global Overview

Current Status
Mangroves are a globally rare group of plants, presently covering an area of about 150,000 km$^2$ (FAO 2007). This coverage represents <1% of all tropical forests worldwide, and <0.4% of the total global forest estate (39,520,000 km$^2$; FAO 2006). There are no global or even regional maps which show the “original” distribution of mangroves with sufficient resolution and degree of confidence (Adeel and Pomeroy 2002), however it is estimated that global mangrove area was once more than 200,000 km$^2$ (Giri et al. 2011). Current coverage is obviously a considerable decline from this original estimate and is largely due to human activities; including direct conversion for others uses (Spalding et al. 2010).

Today, mangroves are found in 123 countries, but only 12 contain >68% of all mangrove forests (Spalding et al. 2010). Indonesia dominates, housing >20% of the world’s mangroves.

Countries with the largest mangrove areas in the world. Together, these countries account for more than approximately two-thirds of global mangrove coverage. (Data from Spalding et al. 2010)

As you can see from this chart, countries in South and Southeast Asia have large mangrove areas. This is because the environmental conditions in these countries are especially favourable for mangrove growth. Globally, the majority of mangrove area is found in the regions of Southeast Asia, South America, North and Central America.
Mangrove forests are dynamic ecosystems that exhibit gains and losses as a result of expansion into new coastal sediments or dieback due to erosion and storm surges (Spalding et al. 2010). However, the majority of the changes in mangrove coverage that have occurred over the last several decades can be attributed to man. Globally, high population pressure in coastal areas has caused the conversion and decline of mangroves. Some experts have even cautioned that the long-term ecosystem services that mangroves provide will likely be lost within the next century as mangrove areas become smaller and more fragmented (Duke et al. 2007).

Approximately 90% of all mangroves grow in developing countries (Duke et al. 2007). In 2007, the Food and Agriculture Organization of the United Nations (FAO) conducted the most comprehensive assessment to date on the changes in global mangrove area over the last 25 years. With the exception of Australia, the FAO (2007) report concludes that there have been extensive losses in all regions since 1980. A full fifth of all mangroves have been lost, while many that remain are in a degraded condition. The global rate of decline over this time frame is reported as follows:

- 1.04 % during the 1980s
- 0.72% during the 1990s, and
- 0.66 % from 2000 to 2005
Estimated declines (km² and %) in mangrove area by region between 1980-2005
(Source: Van Lavieren et al. 2012, Data from FAO 2007).

Although it appears this rate has been decreasing over time the trend is still cause for serious concern considering the limited distribution of mangroves.

There is substantial variation in the rate of decline among countries. In some countries, the extent of loss has been much higher than regional norms; for example, Pakistan, Honduras, the Democratic Republic of Congo, Vietnam, Sierra Leone and El Salvador each lost >40% of their 1980 coverage by 2005 (FAO 2007). However, in Australia, Bangladesh, Cuba, Suriname, Brunei Darussalam, Turks and Caicos Islands and French Guiana the extent of loss has been <1% over the same period. The variation between countries can be mostly attributed to national policies and legal protection. For example, the FAO data show that since 1980, Indonesia has lost some 31% of its mangroves, whereas Malaysia has lost only 16%. This may be largely due to the fact that the majority of Malaysia’s forests fall within a national forest reserve network and many mangroves are actively managed, whereas in Indonesia, mangroves are under extreme pressure from conversion to agriculture, aquaculture and coastal development. There is also variation in the degree of degradation of mangrove forests. For example, in Sundarbans, in 1959 the 78% of mangroves had dense closed canopies, but by 1996 this statistic dropped to 0.2% (Siddiqi 2002).

Global Overview of Threats to Mangroves
Mangrove forests are among the most threatened habitats on earth (Valiela et al. 2001). Worldwide, human activities have been the primary driver of mangrove degradation, destruction and loss. While the major type of threat varies from region to region a common perception in the last few decades seems to be that mangrove forests are a low-value space. Additionally, human-induced degradation compounds
the effect of natural disturbances, which also can have large impacts on mangroves. Global forest destruction and degradation are likely to continue or worsen, unless drastic measures are taken to protect these fragile ecosystems (Kathiresan and Bingham 2001).

A. Conversion by man

i. Urban, infrastructure and tourism development

Extensive areas of mangrove forest have been lost to urban expansion, tourism development, and other infrastructure needs (Spalding et al. 2010). Mangroves have been cleared for urban expansion in a number of major cities including Singapore, Jakarta, Bangkok, Rangoon, Kolkata (Calcutta), Mumbai (Bombay), Lagos, Maracaibo, Recife, Free town, and Douala. Clearing of mangroves for tourism development has occurred extensively in Central America, the Caribbean, and some parts of Southeast Asia and the Middle East. In these areas large tracts of mangroves have been converted to waterfront property, marinas, tourist resorts and golf courses.

![Land reclamation for tourist infrastructure development, the Philippines](Image)

(Credit: Mark Spalding)

Even in cases where mangroves are not entirely cleared, development activities can still negatively affect forest health.

Mangroves thrive in areas that receive freshwater run-off and tidal water flushing. The building of infrastructure such as roads, sea defences and drainage canals can create barriers to natural water flow (Spalding et al. 2010). This can have a devastating effect on mangroves because regular flushing with saltwater or freshwater prevents the hyper-salinization of the mangrove environment and protects the supply of nutrients and sediments. Together, the obstruction of both tidal and freshwater flow results in increased salinity of the mangrove environment and leads to reduced forest growth.

Human precautions to cope with climate change may increase the amount of development in the coastal zone. In order to cope with rising sea-levels, heavy engineering is often used to increase the
elevation of land through infilling (often with materials dredged from offshore), or to build sea defences to protect against coastal erosion. Both of these methods incurs considerable financial costs, and often provides an only temporary solution (Spalding et al. 2010). The rate of sea-level rise associated with climate change is expected to increase in the coming decades, which will further exacerbate these challenges.

ii. **Aquaculture**

Aquaculture, which often involves the creation of extensive pond systems in intertidal areas, is largely responsible for the worldwide losses of mangroves. Expansion of shrimp culture has contributed to approximately 38% of global mangrove loss (Valiela et al. 2001). When losses attributable to fish culture are considered alongside shrimp culture, altogether, aquaculture is responsible for more than half (52%) of global mangrove losses (Valiela et al. 2001). Farmed (or aquaculture) shrimp has skyrocketed in the last decade and now accounts for more than 50% of global shrimp production (see image below, Asche et al. 2011). Almost 80% of the world production of farmed shrimp occurs in the Asia-Pacific region (Wolanski et al. 2000).

The majority of shrimp farms in Southeast Asia, including Thailand, Vietnam and the Philippines are situated in mangroves forests and wetlands (Thu Ha et al. 2012). Between 1980 and 2005 total mangrove area in Asia declined by 25% (FAO 2007).

In Indonesia and Malaysia- the two countries with the largest mangrove area in the region- clearing for aquaculture represents a major cause of this decline (FAO 2007). However conversion for aquaculture has also been a problem in other areas of the world, particularly South America. Since the 1980’s many countries in South America have experienced high losses of mangroves, partly due to conversion for shrimp ponds (FAO 2007). Besides the direct destruction of mangrove forests, intensive shrimp aquaculture has other serious environmental costs:
High yields in intensive shrimp farming can only be maintained through the heavy application of antibiotics, pesticides, and fungicides. This results in contamination of surface and ground waters in the form of excess lime, organic wastes, pesticides, chemicals, and disease microorganisms which flush into neighbouring mangroves and environments (Primavera 1991, Valiela et al. 2001). This can have cascading effects:

- Waste waters from shrimp ponds are rich in nutrients hence eutrophication may occur in receiving waters (Wolanski et al. 2000).
- Shrimp ponds are not sustainable over the longterm. In Thailand, industry estimates of pond viability are from 7-15 years, but in practice shrimp producers often abandon ponds whenever yields or profits drop (Flaherty and Karnjanakesorn 1995) due to:
  - Pollutant levels become too high.
  - Disease outbreaks, e.g., pond-side losses due to the white-spot syndrome virus (WSSV) in 1996 in Thailand alone reached approximately 70000 metric tonnes, valued at over half a billion US dollars (Flegel and Alday-Sanz 2007).

- Mangrove soils are often acid sulphate rich and reclamation for shrimp culture often leads to abandonment after a number of years when pond waters become too acidic (Flaherty and Karnjanakesorn 1995). In some cases very few trees are able to recolonize the area even 10 years after shrimp ponds were abandoned (Wolanski et al. 2000).
  - Abandoned ponds cannot be restored unless extensive efforts are made to rehabilitate soils (Spalding et al. 2010) which leads to continued clearance of mangroves for new ponds.

- Ponds are dependent upon natural populations of shrimp for stocking, i.e., natural larvae which arrive from incoming tides or wild-caught larvae. This results in:
  - Decimation of wild prawn post-larvae populations (Páez-Osuna 2001)
  - Harvest of wild larvae can result in high levels of bycatch of other important fishery species which are discarded – e.g., wild larvae harvested in the Indian Sundarbans can constitute as little as 0.25% of the total catch (Sarkar and Bhattacharya 2003)
  - Intensive aquaculture systems depend on purchased feeds, often created from wild-caught fishmeal (Primavera 1991).

- Wild fish is caught and being overfished as used as as fish feed for the carnivorous shrimp being raised in Aquaculture ponds.

To control salinity levels in ponds large amounts of freshwater are required (Primavera 1991). In areas where huge amounts of freshwater are extracted from underground aquifers the emptied aquifers are subject to saltwater intrusion. This may pose serious threats to local drinking water supplies and agricultural crops requiring freshwater for irrigation.

iii. **Agriculture**

The flat and rich organic soils of mangrove forests have made them prime locations for conversion into cash crops, especially rice paddies and palm oil plantations. When mangrove areas are converted for agricultural purposes they are first deforested. Water from rain removes salt from the soil and costly
embankments are constructed to protect the area from seawater intrusion. When the soil salt levels are sufficiently low, the area is then ready for cultivation. However, this conversion is generally not profitable due to the high cost and low return income (Spalding et al. 2010). Deforestation and alteration of natural hydrology can cause mangrove soils to dry out and become irreversibly acidic. Such soils are no longer useful for growing crops. Additionally, clearing of mangroves for agriculture can lead to a loss in soil elevation. This requires engineering interventions to prevent flooding. For example, in Guyana, large tracts of mangroves have been converted for agriculture – although highly productive, many areas are at or below sea level, requiring building and maintenance of sea walls to prevent invasion of seawater into crops (Spalding et al. 2010).

B. DEGRADATION

i. Grazing by animals
Buffaloes, sheep, goats and camels are kept as livestock in some dry, coastal areas of Asia and the Middle East. These animals often graze on mangroves because of the palatability of their leaves. Grazing can cause significant damage to mangrove plants (Van Lavieren et al. 2012).

ii. Pollution
Pollutants from agricultural and urban runoff, sewage, industrial waste and oil spills, often end up in mangrove forests either directly or indirectly. Mangroves can tolerate levels of pollution that would be detrimental to more sensitive ecosystems like coral reefs; however, their resistance to pollution should not be overestimated. Oil and gas exploration, petroleum production, and oil spills by large tankers are known to harm mangrove ecosystems. The indirect effects of oil pollution on associated mangrove organisms cannot be ignored either. Oil contamination can damage animals living in the mangal, both in the sediments and on submerged mangrove roots (Mackey and Hodgkinson 1996).

High levels of organic pollution can contribute to disease, death and changes in species compositions within mangrove forests (Tattar et al. 1994). Although mangroves have even been used to act as natural biofilters for sewage (Yang et al. 2008); discharge of this nature can also be harmful to mangrove ecosystems. For example, prolonged exposure to high concentrations of excess sewage discharge can kill pneumatophores of Avicennia marina (Mandura 1997). The loss of the pneumatophores decreases surface area for respiration and nutrient uptake and retards the growth of the trees. Pollution can also have cascading effects on invertebrate populations (Sanches and Camargo 1995).

iii. Alteration of natural water flow
Mangroves thrive in areas subject to freshwater runoff and regular tidal flushing. These conditions prevent the salinization or hyper-salinization of soils and ensure a constant supply of new sediments and nutrients (Spalding et al. 2010). Alteration of natural hydrological flows near mangrove forests via the construction of roads, dams, drainage canals, sea defences or other infrastructure leads to reduced freshwater input and restricted tidal flows, which causes drying, and hyper-salinization of mangrove
soils. Declining freshwater supply—due to upstream dams and irrigation schemes, for example—can stress or kill mangroves. In the Indus Delta in Pakistan, total freshwater flows have been reduced by 90%, causing considerable losses of mangrove biodiversity and changes in structure and function.

The bare ground on the landward margin of this road in Brazil has lost all its mangroves as a result of changes in water flow.

(Credit: S. Baba)

iv. **Overharvesting**
While harvesting of mangrove products (e.g., for firewood, construction material, animal fodder, wood chip, and charcoal) has taken place for centuries, in some parts of the world it is no longer sustainable. As communities have grown and became more structured, uses of mangroves have become larger scale and even industrial. Mangrove products are often harvested without any clear management framework or quota, leading to unsustainable harvesting levels and diminished yields.

For example, in Sarawak and Sabah of Malaysia, vast areas of mangroves were once denuded by the wood chip industry (Chong 2006). In Sarawak, one wood chip plant removed 15,000 hectares of mangroves in 25 years. In Sabah, two companies removed 70,000 hectares of mangroves in 15 years (Chan et al. 1993). These operations were eventually recognized as both economically and ecologically unsustainable and are no longer functioning (Chong 2006).

v. **Overfishing**
Mangroves are of considerable importance to artisanal and commercial fisheries because they are critical habitats for many exploited fish and crustacean species (Spalding et al. 2010). Additionally, these habitats provide important nursery areas for some economically valuable offshore fish species. Overfishing is already a serious problem in many offshore fisheries and overharvesting of mangrove species is becoming increasingly widespread. Overfished populations of mature fish/crustaceans both within mangroves and in associated mangrove habitats can lead to reduced numbers of juveniles to replenish adult populations. For example, annual captures of wild-caught penaeid shrimps from
countries with mangroves showed a gradual decline since the early 1980s – catches in 2006 were some 30% lower than in 1980 (Alongi 2009). A decline in wild caught populations could drive the further clearing of mangrove forests for shrimp aquaculture.

vi. **Natural impacts**

*Mangroves forests are also influenced by environmental factors. Extreme weather and wave action, changes to sedimentation and plant diseases can greatly alter forest structure and function. Here, we examine the potentially adverse effects of each of these environmental factors.*

**Extreme weather events and wave action:** Mangroves can absorb and reduce the impact of strong winds, storm surges, and floods that accompany tropical storms, but are sometimes severely damaged. For example, hurricanes have permanently shaped the structure of mangrove forests in the Florida Everglades (Smith et al. 2009). Tsunamis can also be highly destructive to mangrove forests. During the 2004 Indian Ocean Tsunami, mangroves in some areas were overwhelmed and lost. In Lhoknga and Lampuuk, Aceh, Indonesia, a large area of mangroves and other vegetation was destroyed by the wave (Kerr and Baird 2007).

**Sedimentation:** Mangroves thrive in areas with shifting sediments, such as deltaic systems, but are also active colonizers of new sediments (Spalding et al. 2010). However, rapid input of excess sediment can smother and kill mangroves. For example, in 1998, Hurricane Mitch caused massive amounts of sediment transport along the coastline of Honduras. In areas where sediments raised soil elevations by 15 cm, mangroves were not adversely affected (Cahoon and Hensel 2002). In contrast, mangroves in areas which received 50-100 cm of new sediment were smothered and died (Cahoon and Hensel 2002). Regeneration was observed following this event, but it demonstrated that excess sediment can have a strong influence on mangroves.

**Disease:** Disease can cause major damage to mangrove plants. For example, in Bangladesh, top dying disease at one point damaged about 45 million *Heritiera fomes* (Sundari) trees – nearly 20% of the entire Sundarbans forest (Hussain and Acharya 1994). This disease may be caused by an array of factors - increased soil salinity due to reduced water flow, reduction in periodic inundation, excessive flooding, sedimentation, nutrient imbalances, pathogenic gall cankers, and cyclone – induced stress. Although globally, diseases are not a major cause of whole forest mortality, they may afflict mangrove forests weakened by other physical changes (Jimenez et al. 1985).
1.2.1 Regional and Local Threats

Threats to mangroves throughout WIO countries are similar and are mostly human mediated. This is largely attributed to the misconceptions that mangroves are unproductive and non-conducive environments that can be foregone for other uses. The area of mangrove in the WIO region that has been lost over the last century is estimated to exceed 50% of the current area (FAO 2002).

Direct causes of mangrove degradation include tree felling for firewood and building materials, clearance of mangrove areas for agriculture, aquaculture and solar salt works, urban and tourist development, and human settlement (Abuodha and Kairo 2002). While harvesting of mangrove wood products has traditionally continued for long, in some parts of the region it is no longer sustainable and unfortunately, permits for mangrove extraction are granted without any clear plan or process (Kairo 2003), and occur alongside illegal harvesting. Clearance and pollution linked to urbanization and growing coastal tourism are also major threats to mangroves; with oil spills being a particular problem near Mombasa, and clearances for salt pans and aquaculture ponds occurring near Ngomeni (Ungwana Bay). Other causes include reduction in freshwater flow (both surface and groundwater), heavy/increased sedimentation and pollution. In many major rivers in the region, water abstraction for irrigation and power generating dams have reduced the amount of water reaching the mangroves in the estuaries and deltas, altering the optimal habitat conditions for succession. Increased erosion due to land based deforestation is associated with increase in the amount of sediment in rivers that overcome the mangrove forest’s filtering ability, leading to degeneration.

The underlying root causes of the loss and modification of mangroves in WIO are associated with population pressure, poor governance, economic pressure in the rural and urban centres, poverty status of local communities and unequal distribution of resources. In addition, climate change related factors such as sea level rise and increased sedimentation have affected the fringing mangroves in Kenya, Tanzania and Mozambique (FAO 2001). These have led to loss of mangrove cover, shortage of harvestable mangrove products, reduction in fisheries, shoreline change, pollution, loss of livelihood and increase in poverty (UNEP 2003).

All mangroves were declared as government reserved forests through Proclamation No. 44 of April 1932; and are managed by the Ecosystem Managers (EM) of the 5 counties containing mangroves. They are responsible for forest protection and the issuing of harvest permits although as noted, this has not prevented continuing degradation (Kairo 2003). There have been some efforts at reforestation or rehabilitation, notably in Gazi Bay and in Mida Creek at the southern end of Watamu Marine National Park. Protected areas are extensive in Kenya and a number of these sites contain mangroves - including two declared as UNESCO biosphere reserves Kiungu and Mida creek (Spalding et al. 2010).
Top: African countries with the largest mangrove area; Bottom: Changes in African area of mangroves
(Source: FAO 2007)
Clear-felling for charcoal making is widespread in Ruvu Estuary, Tanzania
(Credit: Mwita Mangora)

Expanding coastal development and reclamation for salt pans in Dar es Salaam threatens mangrove at Kunduchi
(Credit: Mwita Mangora)
1.3 Benefits and Human Uses of Mangroves

Importance of mangroves
Many communities around the world have a long history of mangrove use. The riches of mangroves have attracted people on every continent over the course of thousands of years. Indigenous communities have depended upon mangroves for traditional and commercial uses. For many of those that live within or near mangroves, these forests provide critical ecosystem goods and services. Mangroves support the livelihoods of many people by providing food species to eat, fuel to cook and heat, wood to build homes and a place to pursue commercial activities. In addition, mangroves protect coastal communities from storms, improve water quality, are a source of spiritual insight and inspire rich cultural traditions.

In a number of areas, traditional communities living near or even within mangrove habitats have maintained a symbiotic relationship that is often sustainable and even integral to the ecology and functioning of both the mangrove ecosystem and the community. In most places, however, commercial and high-intensity uses have changed the nature of this relationship. Unfortunately, many of these societies, once dependent on mangroves for valuable services, have chosen to overlook the long-term benefits that mangroves provide, allowing rapid degradation or entire loss of mangroves.

Ecosystem services are the benefits people derive from ecosystems (MEA 2005). These benefits are often overlooked, however, resulting in the degradation or loss of mangrove forests, at considerable cost to society. These services have been categorized as provisioning, regulating, cultural and supporting in nature (MEA 2005). In this section we will focus on provisioning mangrove services; the tangible products (or goods) that they provide to people. People derive many uses from mangroves and while some uses of mangroves are benign – meaning that they have little or no harmful effects, others can be very destructive (Clough et al. 2013). It is critically important for the future of both mangroves and human societies that the roles and values of mangroves are properly evaluated and understood.

Ecosystem Services as described by the Millennium Ecosystem Assessment
Definition: Ecosystem services are defined as services provided by the natural environment that benefit people

Provisioning Services are products obtained from ecosystems, e.g., food, fresh water, fuel, wood and fibre
Regulating Services are benefits obtained from the regulation of ecosystem processes, e.g., regulation of climate, disease, flood and water
Supporting Services are those that are necessary for the production of all other ecosystem services. They differ from provisioning, regulating, and cultural services in that their impacts on people are often indirect or occur over a very long time, e.g., soil formation, primary production and nutrient cycling
Cultural Services are nonmaterial benefits people obtain from ecosystems through cognitive development, spiritual enrichment, reflection, recreation, and aesthetic experiences, e.g., cultural diversity, knowledge systems, educational values, social relations, sense of place, cultural heritage and ecotourism.

### Mangrove Goods and Ecosystem Services

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Let’s begin by exploring the products derived from mangrove forests, also known as mangrove ‘goods’

**Mangrove Goods**

Mangrove goods can generally be grouped into products derived from their woody parts, called, timber products, and products derived from their non-wood parts, called, non-timber products.

**Timber Products**

- Construction
The timber of many mangrove species is sought after as building material. This is largely because mangrove wood is relatively durable and resistant to rotting and termite attack (Spalding et al. 2010). Mangrove wood has been used for a variety purposes including housing, boat building and fishing stakes (Ewel et al 1998). Wood is also used for the production of chip and pulp, which is used in the manufacturing of paper and chipboard, as well as the conversion of rayon in the textile industry (Spalding et al. 2010). Unfortunately, large-scale woodchip and pulp manufacturing operations have been very destructive in some of the forests of South Asia (Clough et al. 2013, Ong and Gong 2013). Moreover, most commercial timber operations in mangroves have been unsustainable in the long-term (Clough et al. 2013). Exceptions to this are operations in the Sundarbans of India and Bangladesh, in West Malaysia and in a few countries in Central America (Clough et al. 2013).

Mangrove poles for construction destined to local markets in Zanzibar
(Credit: Mwita Mangora)

- **Fuel**
Harvest of mangroves for fuelwood occurs throughout the tropics (Baba et al. 2013). Some tree species, notably those of the family *Rhizophoraceae*, produce wood that burns with a high calorific value (Baba et al. 2013). Because of this, mangroves provide an abundant source of firewood and high quality charcoal. Mangrove-derived charcoal is now produced on a large commercial scale (Spalding et al. 2010). Firewood is particularly important in areas where there are no alternative sources of energy (Spalding et al. 2010). While fuel is a critical use of mangrove timber, it is important that harvest of trees for fuelwood occurs on a sustainable basis. One of the best examples of a forest that has been managed sustainably is the Matang Mangrove Forest in Malaysia, where pure and mixed stands of *Rhizophora* and *Bruguiera* have been managed for production of poles and charcoal for over 100 years (Clough et al. 2013, Alongi 2002, Ewel et al. 1998).

- **Wood Crafts**
Certain mangrove species have timber which is soft enough for sculpture. One of the best examples of crafts produced from mangrove wood is the sculptures of the *Mah Meri* people on Carey Island, in
Singapore, Malaysia. Read the case study below for more information on this unique mangrove handicraft.

**Non-Timber Products**

- **Tannins**
  The bark of all mangrove trees, but particularly, those in the family, *Rhizophoraceae* contain large amounts of tannins (Clough et al. 2013). These tannins have traditionally been used to prepare leather, cure nets to extend their longevity, and as dyes for cloth (Spalding et al. 2010, Clough et al. 2013). Small-scale use of tannins still continues in certain areas. For example, in Guyana, Amerindian people harvest mangrove bark to sell for tannin production (Allan 2002). Tannins are used to produce leather from sheep and cow hides (Allan 2002). In the Pacific Islands the bark from *Bruguiera gymnorhiza* and *Rhizophora stylosa* is used to dye cloth made from the inner bark of plants, called, “Tapa” (Day 2000, Murofushi and Hori 1997). Synthetic tannins are now more commonly used than those derived from mangrove bark (Spalding et al. 2010).

- **Roofing from the Nypa palm**
  Throughout coastal communities in Asia, the leaves of the *Nypa* palm are used to make thatching and walls for homes (Clough et al. 2013). Although thatching has limited durability, it is cheaper than alternative materials and is commonly used by poorer households (Clough et al. 2013). *Nypa* leaves are also used to make mats, baskets and cigarette wrappers (Clough et al. 2013).

- **Food**
  Different mangrove plants are consumed by coastal communities all over the world. The fruits of Sonneratia, Bruguiera, Kandela and Avicennia are commonly used for food purposes (Spalding et al. 2010). For example, in Sri Lanka, the fruit of *Sonneratia caseolaris* is used to make juice (Jayatissa et al. 2006). In Indonesia, these fruits are also harvested to make syrup (Baba et al. 2013). In the Pacific Islands, propagules of Bruguiera gymnorhiza are cooked and eaten (Baba et al. 2013). The most commonly used food products are harvested from Nypa (Spalding et al. 2010). Its sweet sap can be used to make sugar, as well as alcohol and vinegar after fermentation (Spalding et al. 2010). The endosperm of the Nypa fruit can be consumed directly, and is gathered for commercial sale (Ng et al. 2001).

The nectar of mangrove plants attracts honey bees, which facilitate apiculture activities in some regions. Wild beehives may be harvested opportunistically (Clough et al. 2013) or beekeepers may move their hives in close proximity to or between mangroves stands, so that the bees can forage on their flowers (Breadbear 2009). Commercial-scale honey production from mangroves occurs mainly in Florida, Cuba, Guyana, Vietnam and the Sundarbans of India and Bangladesh (Spalding et al. 2010, Baba et al. 2010, Hamilton and Snedaker 1984). In the 1980’s around 2,000 people were reported to be involved in producing over 1,000 tons of honey from the Indian Sundarbans (Untawale 1987).
• **Fodder**
Mangrove vegetation is harvested and used as fodder in parts of Asia and the Middle East. Both the foliage and propagules are fed to livestock (Baba et al. 2013). Stands of *Avicennia* are grazed widely by camels in Pakistan and the Middle East, and goats, buffalo and cattle in parts of Asia (Hamilton Snedaker 1984). Grazing by camels can damage large areas of mangroves (Clough et al. 2013). Particularly in the Middle East, browsing by camels has caused the degradation of large mangrove stands (Baba et al. 2013). Their feet trample seedlings and pneumatophores (Baba et al. 2013). In Pakistan extensive camel grazing has caused widespread defoliation and stunted the growth of *Avicennia* (Clough et al. 2013).

• **Non-wood Crafts**
In some coastal communities the non-wood parts of mangroves are used to produce traditional handicrafts. For example, women of the *Mah Meri* people weave decorative items similar to Japanese origami from leaves of *Nypa fruticans* (Baba et al. 2013). These crafts are used to adorn altars, homes, spirit huts and dancers (Rahim 2007). On islands of the Pacific, flowers of several mangrove species, including *Bruguiera sexangula*, *Bruguiera gymnorrhiza* and *Lumnitzera littorea* are used as leis and garlands (Allen 1998, Steele 2006).

• **Medicine**
In the developing world, the majority of mangrove areas are inhabited by rural communities which may have limited access to medical facilities (Bandaranayake 1998). Therefore, mangrove plants are widely used by forest dwellers for bush medicine (Bandaranayake 1998). Coastal people which live in or adjacent mangroves use products derived from these plants to treat a variety ailments including diarrhoea, epilepsy, rheumatism, asthma and diabetes, among many others (Bandaranayake 1998). Extracts from mangroves are still used primarily in indigenous medicine and their potential as commercial pharmaceutical agents is now being explored (Bandaranayake 1999).

### Mangrove Services

**Introduction**
Mangrove ecosystems provide a wide range of valuable services for animals and for humans. The benefits that people derive from mangroves are not always tangible. As a whole, the mangrove ecosystem provides many regulating, supporting and cultural services which are not always obvious or easily measured. In this lesson, we explore these important mangrove services.

• **Recreation and Tourism**
Because they are located along coastlines and have unique aesthetic and ecological characteristics, mangrove ecosystems provide excellent opportunities for recreation, ecotourism and environmental education (Walters et al. 2008). This potential has not always been recognized. Mangroves have historically been shunned by tourists because they are considered hard to access, are infested with mosquitoes and their soils emit foul odors (Spalding et al. 2010). However, perceptions are changing and in many countries mangroves are being used for tourism activities (Spalding et al. 2010). Mangrove eco-
tourism activities include strolling on boardwalks, kayaking, canoeing, wildlife watching, boat tours and fishing (Van Lavieren et al. 2012). In particular, the mangrove offers exceptional opportunities for wildlife watching (Ong and Gong 2013). For this reason, some mangroves attract a large number of visitors, such as the Caroni swamp in Trinidad, where tourists come to view thousands of scarlet ibis that congregate each evening in the trees (Spalding et al. 2010).

- **Biofiltration**

Several properties enable mangrove systems to remove excess nutrients and pollutants from contaminated water sources. Mangrove vegetation is highly productive and can filter nutrients from water (Kathiresan and Bingham 2001). Extensive root systems slow the movement of water, promote settlement of particles (Wolanski 1995, Young and Harvey 1996) and bind particles in the substrate (Alongi 2005). Sediments have a high capacity for retaining heavy metals (Kathiresan and Ajmal Khan 2011) and absorbing nutrients from sewage (Tam and Wong 1995, 1996) and shrimp pond effluent (Trott et al. 2004). As a result, mangrove forests have been proposed as suitable for the treatment of sewage and aquaculture effluent and have historically been favoured sites for sewage disposal (Robertson and Phillips 1995, Wong 2007). There has been extensive research into using mangroves to treat wastewater (Yang et al. 2008) and aquaculture effluent (e.g., Robertson and Phillips 1995, Shimoda et al. 2005, Tam 2006). For the treatment of aquaculture effluent, it has been estimated that between 2 and 22 hectares of mangrove forest would be needed to filter nitrogen and phosphorus loads from effluent produced by a 1 hectare shrimp pond (Robertson and Phillips 1995).

Although mangroves are somewhat tolerant to wastewater pollution, there remains great concern over their use as sites for sewage disposal (Cannicci et al. 2009). The effects of sewage disposal on mangrove ecosystems will not be uniform; it will depend on the quantities of sewage, the duration of dumping, and the characteristics of each forest (Kathiresan and Bingham 2001). The distribution and diversity of wildlife in mangroves is sensitive to a variety of chemicals and nutrients (Cannicci et al. 2009). Wastewater dumping in mangroves could result in major changes to faunal communities (Cannicci et al. 2009). In high concentrations, organic pollutants and excess nutrients can impair growth and even kill mangroves (Tam et al. 2005, Duke et al. 2005, Lovelock et al. 2009). There needs to be more research into the tolerance of mangroves to organic pollution and caution in their use as sites for waste disposal.

- **Coastal Protection**

Mangroves play an important role in shoreline protection under normal sea conditions and during tropical storms and hurricanes (UNEP-WCMC 2006). As such, they are increasingly being promoted and used as a tool in coastal defense strategies (McIvor et al. 2012a). Around the world, many mangrove plantation projects have been undertaken on the basis of improving coastal protection (Spalding et al. 2010). Due to their complex structure, particularly their aerial roots, the presence of mangroves can attenuate waves and reduce the impacts of storm surges (McIvor et al. 2012ab). It has been reported that mangroves can reduce the height of wind and swell waves by up to 66% over 100 m (McIvor et al. 2012a) and reduce the water level of storm surges between 5 and 50 cm per km of mangrove width.
(McIvor et al. 2012b). By reducing wave energy, mangroves also prevent sediments from being washed away and decrease shoreline erosion (Mazda et al. 2007, Thampanya et al. 2006). Diminished energy of incoming waves also lessens the risk of flooding to communities which live behind mangroves (McIvor et al. 2012a).

Damaged boat jetty and intact mangrove forest at the Vellar Estuary after the Tsunami
(Credit: Spalding et al. 2010)

- Climate Change Mitigation

Deforestation is a major source of greenhouse gas (GHG) emissions, particularly carbon dioxide (CO$_2$) (IPCC 2007b). Mitigation refers to human interventions to reduce the sources of or enhance the sinks for GHG (IPCC 2007c). Maintaining and improving the ability of forests to absorb and sequester carbon is an essential component of climate change mitigation (Chhatre and Agrawal 2009). Mangroves are one of the most carbon-rich tropical forests and have extremely high carbon storage rates (Donato et al. 2011). These forests store more carbon per hectare than other vegetative coastal ecosystems (e.g., saltmarshes and seagrasses) (Murray et al. 2011). There is potential for large-scale emissions from the degradation and conversion of these systems (Murray et al. 2011). As such, halting the current decline and restoring degraded areas of mangroves may form an important part of some countries climate change mitigation efforts.

Because they store large amounts of carbon and are threatened by the financial appeal of conversion, mangrove ecosystems are an ideal target for carbon financing (Murray et al. 2010). Creating credit schemes for carbon stored, sequestered or released from mangroves, saltmarshes and seagrasses (“blue” carbon – Herr et al. 2012) is an incentive-based method that can provide financial motivation to protect such habitats. The opportunities and limitations of current international policies and economic markets to accommodate such credit schemes are being evaluated (e.g., Murray et al. 2010, Crooks et al. 2011, Herr et al. 2012, Murray and Vegh 2012). Additionally, many field projects around the world are in the process of demonstrating that the climate change mitigation value of these ecosystems can motivate their conservation and/or restoration (Bredbenner 2013). The creation of carbon credits
through the conservation of mangroves could contribute to poverty alleviation and biodiversity conservation in tropical coastal areas (Blue Ventures 2012).

- **Wildlife Habitat**
Mangrove forests are unique ecosystems which provide habitat to a broad diversity of plants and animals both large and small. From the leafy canopy, to the muddy intertidal banks, and aerial roots which extend into the water, the forest offers many environments for animals to exploit. The main groups of animals found in the mangrove include sponges, prawns, insects, fishes, amphibians, reptiles, birds and tiny animals which live in and on the sediments (Nagelkerken et al. 2008). Birds roost in the canopy, shellfish attach themselves to roots, and snakes and crocodiles use them as hunting grounds. Many bird species use mangroves as nesting or roosting grounds, including terrestrial and marine species that may feed in adjacent ecosystems.

![Mangrove provide nesting and roosting areas for numerous species.](Credit Mark Spalding and Hanneke Van Lavieren)

Other marine species use the complex structure of the mangroves as shelter from predators, spreading quickly through the shallow waters of rising tides into areas where larger predators cannot easily reach. The roots of mangroves provided hard substrate for bivalves, such as oysters to settle on and can be abundant on mangrove roots.

![Below the water mangrove roots provide habitat for many species](Credit: U.S. Geological Survey/ Caroline Rogers)
Many species which are restricted to the mangrove are threatened or vulnerable due to human activities in the coastal zone. In fact, it has been reported that more than 40% of mangrove-endemic vertebrates are globally threatened (Luther and Greenberg 2009). There are examples of this from around the world: the proboscis monkey of Borneo (*Nasalis larvatus*) (Meijaard et al. 2008), the pygmy three-toed sloth (*Bradypus pygmaeus*) of Panama (Anderson et al. 2011), the mangrove finch of Ecuador (*Camarhynchus heliobates*) (Birdlife International 2012) and the mangrove frog of Haiti (*Eleutherodactylus caribe*) (Hedges and Thomas 2010). For animals such as these, loss of the mangrove habitat may lead to extinction from the wild.

In addition to contributing to global biodiversity, mangrove wildlife also supports people’s livelihoods. For example, some animals are hunted or gathered for direct consumption or sale (e.g., fish and shellfish - discussed more in the next section), while other unique animals provide opportunities to generate income from ecotourism. Wild food products are particularly important for sustaining the livelihoods of the poor (Scoones et al. 1992).

**Nutrient Cycling**

Mangroves play an important role in nutrient cycling in coastal ecosystems (Kristensen et al. 2008). These forests are often nutrient poor (Kristensen et al. 2008), but maintain high rates of productivity through efficient nutrient cycling and nutrient conservation (Kristensen et al. 2008). They produce large amounts of tree litter, and particularly, leaf litter (Kathiresan and Bingham 2001). The decomposition of this litter contributes to the recycling of nutrients within the mangrove as well as adjacent habitats (Kathiresan and Bingham 2001).

The nutrient cycle starts when the leaves fall from the tree into the water or on the muddy banks and microbial decomposition and leaching begin (Kathiresan and Bingham 2001). During leaching, water-soluble components in the leaves, such as tannins, carbohydrates and potassium are drained away. Fungi and bacteria then colonize the litter and greatly contribute to the decomposition process, as well
as the transformation of nutrients (Kathiresan and Bingham 2001). The feeding activity of mollusks and crustaceans also enhances litter decomposition and nutrient flow (Kathiresan and Bingham 2001).

While some mangroves retain the majority of detritus within their sediments, others export a large portion of this to adjacent waters through the movements of the tide (Kristensen et al. 2008). Therefore the organic detritus and nutrients produced in the mangrove may not only support productivity within the forest, but could also enrich adjacent coastal waters (Kathiresan and Bingham 2001). For example the flow of particulate organic matter between mangroves and adjacent seagrass meadows may be tightly linked (e.g., Hemminga et al. 1994).

**Fisheries and Aquaculture**

Mangroves are critical habitats for coastal and marine fisheries (Spalding et al. 2010). Mangroves support fisheries all over the world: In the Gulf of California, mangrove-associated fish and crab species account for 32% of small-scale fisheries landings in the region (Aburto-Oropeza et al. 2008); approximately 75% of commercial fish species caught in the West African Marine Eco Region depend on mangroves for reproduction and as nurseries for their young (USAID 2009) and mangroves and associated habitats in Queensland, Australia support 75% of commercial fisheries (Manson et al. 2005a). Aside from providing nutrition, fisheries in and around mangroves provide direct employment to 0.5 million fishermen and 1 million jobs for small-scale fishermen globally (Matthes and Kapetsky 1988). Therefore, the importance of mangroves in supporting fisheries which provide food, employment and income to coastal people cannot be overstated.

Several aspects of the mangrove environment contribute to its fisheries support function. High rates of primary production provide a rich source of nutrients, aerial roots create a complex three dimensional habitat that, combined with a complex system of channels and pools, provide shelter for many species (Spalding et al. 2010). Trees which grow or extend into the water column provide hard substrata in an otherwise soft sediment environment (Ellison and Farnsworth 1992) and allow colonization by a variety of edible mollusks (e.g., mussels, oysters and cockles). These mollusks, as well as shrimp and crabs are gathered from among the mangrove roots. The mangrove waterways and adjacent lagoons also support high value finfish species such as mangrove snapper and barramundi (Spalding et al. 2010).

Mangrove associated aquaculture is globally important for providing subsistence-level food and income, as well as commercial benefits for a variety of stakeholders (MacIntosh and Ashton 2005). As the surrounding ecosystem, mangroves support aquaculture operations by providing seed (larvae and juveniles), feed, nursery habitat, clean water and waste assimilation (Rönnbäck 1999, Naylor et al. 2000, Nagelkerken et al. 2008, Kautsky et al. 2000). Even intensive shrimp farms, located far from mangrove areas and fully reliant on hatchery-produced seed, are still dependent on mangrove ecosystems to continuously provide wild female spawners and broodstock (Rönnbäck, 1999). Unfortunately, in recent decades, aquaculture activities have greatly intensified (Rönnbäck 1999) and are responsible for more than half of global mangrove losses (Valiela et al. 2001).
Farming of marine shrimp has been practiced in some Asian countries for centuries (Kungvankij 1985). In these systems, ponds were created in intertidal regions, typically, mangroves (Robertson and Phillips 1995). Ponds were stocked either through harvesting wild shrimp fry or through the natural inflow of the tide into ponds (Robertson and Phillips 1995). Growth of shrimp in the ponds was then facilitated by the natural fertility of the mangrove soils (Robertson and Phillips 1995). There remain good examples of non-destructive, small-scale mangrove aquaculture systems from many countries around the world (below from Macintosh and Ashton 2005).

- Malaysia and Kenya: Mudcrab fattening or grow-out in mangrove pens and cages
- Thailand: Fish cage/ bivalve and seaweed culture in mangrove waterways
- Vietnam: Mixed shrimp-mangrove – crab-cockle systems
- Brazil: Oyster rearing
- Indonesia: Integrated mangrove fish or shrimp farms, called silvofisheries or “tambaks”

The importance of mangroves in sustaining aquaculture and capture fisheries is paramount. Below we summarize the means through which mangroves support these industries (Below adapted from Rönnbäck 1999).

**Capture fisheries**

**Habitat**

- **Food abundance** - The mangrove environment is rich in sources of food. These food sources support important fishery species.
- **Predation refuge** - The complex physical structure of the mangrove provides shelter for both adult and juvenile fish and crustaceans. This function may enhance the number of juveniles which survive to join the adult population which can be harvested.
- **Lateral trapping** - The movement of water within mangroves is often diminished, which means that water is retained for longer in the system. Therefore, the planktonic larvae of many species may be retained in the mangrove.

**Trophic Subsidy**

- **Outwelling** – While large amounts of leaf litter are retained in the forest, a portion may be transported to adjacent coastal areas as nutrients and carbon, potentially supporting the productivity of these systems.
- **Animal migrations** – The juveniles and larvae of some fish and crustaceans which are spawned in adjacent coastal habitats (e.g., coral reefs) use mangroves as nursery grounds. After maturing, these species may migrate out of the mangrove to their adult habitat. Because mangroves may contain a high abundance of juvenile organisms and food items, it attracts larger carnivorous fish species which may move in and out of the mangrove opportunistically to feed.

**Physical Subsidy**
• **Stabilizing salinity** – Mangroves dissipate wave action and lower the energy of water within the mangrove. Because of this, waters in the mangrove can be retained for long periods and therefore the physical properties of the water, such as salinity remain stable, rather than fluctuating.

• **Lowering turbidity, nutrient and pollution levels** – Although mangroves may export part of their productivity to adjacent waters as carbon and nutrients, they also control water quality by trapping and absorbing nutrients, particulate matter and pollutants from river runoff. This function of mangroves can be of major benefit to coral reefs, which thrive in clear, nutrient poor waters.

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**Case Study - Mangroves and Fisheries: Australia**

With 6.6% of the total global mangrove area, Australia is one of the world’s major mangrove nations and some 40 mangrove species have been recorded here. The value of mangroves in supporting coastal and offshore fisheries in Australia is substantial. Trawling for prawns across the wide shallow shelf areas off the coasts of both the Northern Territories and Queensland is a major industry and one of this country’s most valuable export fisheries, bringing in over AU$70 million annually. Although mature prawns are captured far offshore, most commercial species spend their early life stages in mangrove habitats. For example, banana prawns, which make up 50-80% of the total prawn catch, depend on mangroves as critical nursery grounds. Also, the highly prized tiger prawn utilizes seagrass beds which are often found growing adjacent to mangroves (CSIRO 1998, AFMA 2009). Protection of these important nursery habitats is therefore crucial for the longterm sustainability of these fisheries.

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**Aquaculture Insurance**

• **Protection from storms and floods and control of erosion** – By diminishing wave energy and binding sediments, mangroves decrease erosion, stabilize shorelines, and protect coastlines from floods and storms. This protects aquaculture operations from damage by these natural disturbances.

**Water Quality Maintenance**

• **Flood and erosion control, nutrient assimilation and sediment trapping** - Aquaculture operations situated in mangroves are greatly affected by water quality. The ability of mangroves to maintain water quality (i.e., trap sediments, stabilize salinity, assimilate nutrients and remove pollutants) is therefore very important to the sustainability of aquaculture operations.

**Food Input**

• **Detritus and fishmeal** – Nutrients and detritus from the mangrove may be exported adjacent waters where they support mollusk culture operations. In addition, fish and invertebrates which inhabit the mangrove can be harvested for aquaculture feed.
**Broodstock** – Wildcaught adult shrimp and fish are still used as reproductive stock in many aquaculture operations. Mangroves provide a source of broodstock for aquaculture and their deforestation has led to a shortage in supply.

**Seed** – Mangroves naturally have high numbers of larvae and juveniles which are used as “seed” in aquaculture operations. Wild seed may be harvested directly from the mangroves and then developed in aquaculture systems, or it may enter the aquaculture system naturally with the incoming tide.

- **Cultural and Spiritual Benefits**
  Ecosystems have strongly influenced human cultures, religions, social interactions and knowledge systems (MEA 2005). The cultural importance of ecosystems stems not only from the tangible goods and services they provide, but also the intangible and nonmaterial benefits (Verschuuren 2006). Mangroves provide opportunities for religious and spiritual enrichment, artistic inspiration and development of ecological knowledge. In many cultures, the special features of ecosystems, such as rivers, trees or certain animal species obtain special spiritual significance (Verschuuren 2006) and mangroves are no exception to this. These ecosystems have been considered places of worship in many areas of the world.

**Valuing Ecosystem Services**

Economic valuations of mangrove ecosystem goods and services can entice financial investment and provide some of the most powerful arguments for effective mangrove management. Please see 4.6 for more information.

Too often the benefits that ecosystems deliver to humans are only appreciated once they are lost. If mangrove forests are not seen as a fundamental economic and ecological resource to be treasured, they will continue to be over-exploited, degraded and lost. The value of healthy mangrove forests needs to be more widely communicated both to the public and to those policy makers with the capacity to make a difference. In some cases, valuation studies are already providing powerful arguments for investment in sustainable utilisation, protection and restoration of mangrove ecosystems. These successful examples should be better captured and shared to help stimulate such actions.

There are many studies that have tried to quantify various benefits provided by mangroves in financial terms but the areas covered and methods used vary and hence are not comparable. There is considerable variance in the estimated value of mangroves between studies and locations, even for similar services or uses. Much of this variation can be linked to very real differences in social and economic situations in each locality. Wells et al, 2006 provided a summary value of $ 2000 - 9000 per ha/yr for manrove goods and services. This is a good estimate of value for mangroves over wide areas and where they are extensive and where they are close to human populations and already utilized. However this is less realistic for more remote mangrove, low-diversity arid mangrove systems, or for
mangroves utilized primarily for subsistence in poorer countries - where monetary values become somewhat trivial and where human dependence is a more useful measure.

Decision-makers with access to information on the full range of ecosystem service values that mangroves provide will be better positioned to make more efficient and justified cost-effective choices. There is ample evidence that highlights the economic value of mangrove ecosystem services in different regions and under different socio-economic conditions. Still, considerable variance exists in the estimated values among studies because of discrepancies between valuation methods and among locations with differing socio-economic circumstances.

At the present time, some of the most compelling arguments for sustainable management, use and restoration of mangroves, arise from valuations from individual field studies, such as the Matang Mangrove Forest Reserve in Malaysia and Mexico’s Gulf of California, where it is estimated that one hectare of mangroves contributes ~US$37,500 per year to fisheries (Aburto-Oropeza et al. 2008).

### 1.3.1 Uses of Mangroves in the WIO and East Africa

Mangrove wetlands are multiple use systems that provide protective, productive and economic benefits to the coastal communities throughout the tropics. The forest provides timber and non-timber products such as fuelwood, poles, local medicine, and fisheries resources to millions of people in the WIO region (Abuodha and Kairo 2002). Along the Kenya coast, mangroves have been estimated to provide more than 70% of the wood requirement to the people adjacent the forest (Wass 1995). Similar estimates have been made in Madagascar, Tanzania and Mozambique where mangroves provide more than 50% of the wood requirements to the community adjacent the forest (UNEP 2003). Mangroves also protect shoreline erosion and provide safe havens for humans (Spalding et al. 1997). In addition mangrove provides nursery grounds for a number of commercially important fish species, prawn, crabs and other animals, and enhances fishery productivity of the nearby water (Huxham et al. 2004, Mirera et al. 2010).
1.4 Biology and Ecology of Mangroves

Introduction

Mangrove plants are unique colonizers of the intertidal zone. There are few other plants which can survive the challenges posed by life on the boundary of freshwater, marine and terrestrial environments. The physical environment of the intertidal zone is characterized by tidal changes in water and salt exposure as well as variable degrees of oxygen and nutrient availability. Mangrove plants have evolved specialized traits which have arisen from their adaptation to these conditions. These traits are important because they have allowed mangroves to survive on earth for thousands of years to form the complex ecosystems we see today. Additionally, these traits ultimately influence forest-wide properties of structure and function. By understanding mangrove plant traits and the variability with which they are expressed, we can also explain patterns in vegetation structure, animal food webs, ecosystem productivity and connectivity to other environments.

Adaptations to flooding

Overview

Mangroves are shrubs and trees which edge the sea and are regularly flooded by the tide. The magnitude of waterlogging depends on their vertical position on land (i.e., above or below the high tide mark), as well as the amount of freshwater input they receive from rainfall, rivers, groundwater and surface runoff. This regular waterlogging presents major challenges to plant growth. As a result, mangroves have evolved some notable structural and chemical adaptations. In this section we explore why flooding poses challenges and we discuss in detail the unique adaptations mangrove plants have evolved to deal with this.

Before beginning this module, it is important to understand that oxygen is essential to plants so that carbohydrates can be converted into energy through a process called aerobic respiration. While cells in plant leaves get oxygen through photosynthesis, cells in roots usually depend on oxygen from their surroundings to stay alive. Buried roots typically absorb oxygen from small air spaces in the soil. However, this is a problem for mangroves as regular flooding typically results in anoxic conditions (oxygen deficiency) within the root zone (Drew 1992). Low oxygen levels can lead to reduced plant growth because plants cannot generate enough energy to take up the nutrients they need to survive (Gibbs and Greenway 2003). Additionally, anoxic conditions can result in the production of phytotoxins (substances toxic to plants) via microbial activity (Feller and Sitnik 1996). Hydrogen sulphide is a strong phytotoxin, produced by soil microorganisms, which can inhibit aerobic respiration (McKee et al. 1988).

So, how have mangroves adapted to the challenges that flooding creates? Mangroves have extensive above ground root systems (Scholander et al. 1962), root aerenchyma, as well as associated features that allow for internal circulation of air. We will now dig a little deeper into the most obvious of these adaptations: the above ground root system, better known as aerial roots.
Aerial roots

Walking in a mangrove forest, you will quickly notice that mangrove roots often branch and arch into the air and sometimes even stick out of the mud. These roots look very different from those of other tropical forests whose roots are normally hidden underground.

Function of aerial roots

1) Support Structures - Mangrove root systems are supportive structures which help anchor the plant in unstable soils. They allow mangroves to stay upright in soft wet mud because so much of the biomass of a mangrove is concentrated in the roots thereby allowing for a bottom-heavy form, or low ratio of top to root biomass (Komiyama et al. 2008, Komiyama et al. 2000).

2) Oxygen Transport – Mangrove roots need air, which can often be in short supply in waterlogged soils. Their specialized root structures allow for the transport of oxygen in flooded conditions. Lateral branching roots provide support while allowing for shallow root systems (Kathiresan and Bingham 2001). Shallow roots mean that deeper oxygen deprived soils can be avoided (NOAA 2010). In fact, the roots of many species do not penetrate far into the soil as most of the root biomass is found <70 cm deep (NOAA 2010).

3) Gas Exchange – The surface of mangrove roots are covered with specialized structures for gas exchange, i.e., loose air-breathing bunches of cells called lenticels (Tomlinson 1986). When roots are exposed, these surface pores allow the plant to exchange gases with the atmosphere.

Types of aerial roots

Evolution has led to the development of various aerial root formations in different mangrove species (Kathiresan and Ajmal Khan 2011, Spalding et al. 2010).

1) Stilt (or prop) roots: These are supportive structures which allow the tree to stand upright in unstable soils. They consist of looping branch-like roots which grow out of the central trunk and penetrate the soil further away. Tertiary roots sometimes branch off these roots themselves. These roots are also respiratory structures as they allow the transport of oxygen from the atmosphere to the root system via lenticels and internal aerenchyma tissues.
2) **Pneumatophores**: These are roots which extend upwards from sub-surface roots. In some species, these structures are tall and conical, while in others they appear short and narrow. The surface of pneumatophores is covered with lenticels.

3) **Buttress roots**: These are large, shallow roots that extend around all sides of the tree thereby providing structural support. This root morphology is common in many tropical tree species as a strategy for support in shallow soils.

4) **Knee roots**: These are knobby rounded extrusions that branch upwards from sub-surface roots. They are similar to pneumatophores. The aerial portions (knees) of these roots help in aeration of the whole root since they grow upwards out of the anoxic soil so that lenticels are in direct contact with the atmosphere.

![Schematic diagram of types of mangrove roots, stilt (prop), pneumatophores, buttress, knee](Source: Kathiresan and Khan 2011)

We have discussed how oxygen enters the plant through lenticels on exposed roots. Now let's explore the aerenchyma and the role it plays in the exchange and storage of gases.

**Aerenchyma**

The aerenchyma is spongy plant tissue with large air spaces (Evans 2003). It is found in plants which live in flood-prone, aquatic or wetland environments. Mangroves have developed an extensive aerenchyma system. These internal air spaces may comprise >50% of the total volume of mangrove roots anchored in mud (Gill and Tomlinson 1977). They provide an internal pathway for the exchange and storage of gases within tissues and act as a channel for the transport of gas within mangroves from roots to shoots (Visser et al. 1997).

This pathway is important because the survival and ability of mangrove roots to penetrate anoxic soils depends on an adequate supply of oxygen to plant tissues (Armstrong et al. 1991). The oxygen that is stored and transported by the aerenchyma is consumed by cells in adjacent tissues, allowing the continuation of respiration. This oxygen also diffuses towards the rhizosphere, the region of soil directly adjacent to and influenced by the roots, in a process termed radial oxygen loss (ROL) (Armstrong 1979). ROL creates a protective aerobic (air-filled) zone next to the root where phytoxins can be neutralized before entering the root tissue (Armstrong et al. 1992). This process protects the roots from the damaging effects of phytoxins. In a later module we will return to the concept of ROL and explore further why it is such an important process.
Adaptations to salinity

Overview
Excess salt is harmful to plants (Parida and Das 2005). On a global scale, salt restricts plant growth more than any other substance (Zhu 2007). Nevertheless, mangroves are able to grow and thrive in saline environments, conditions which very few other plants can survive. This is because mangroves have evolved special mechanisms to cope with high salinities. Such adaptations are important because they have given mangroves a competitive advantage over other plants and allowed them to dominate the world’s tropical and subtropical coastlines. In this section we review why high salinities limit plant growth and the specialized adaptations that mangroves have evolved.

Challenges posed by saline environments

Let’s begin this section by reviewing the two major challenges that high salinities pose to mangrove growth:

1) Water deficit in cells: Mangroves require water to prevent cellular dehydration. However, soil salinities in mangrove forests range from low to high levels and water moves naturally from regions of low to high salt concentrations through osmosis. In order to prevent dehydration, mangroves have evolved adaptations to retain water within cells against this osmotic gradient.

2) Toxic levels of ions: Sodium (Na⁺) and Chloride (Cl⁻) are the dominant ions found in seawater. High levels can be toxic to mangrove plants as they interfere with cellular protein synthesis, alter respiration rates and inhibit enzyme activity. Mangroves are tolerant to both fluctuations in and high concentrations of salt (Parida and Jha 2010), but in general, grow best under low to moderately saline conditions (Clough 1984; Ball and Pidsley 1995). Optimal salinity levels range from 5-50% of seawater, depending on the species of mangrove and growth conditions (Ball 1996).

Adaptations to saline environments

Now let’s explore the two major adaptations which mangroves have evolved for coping with saline environments: 1) Structural and anatomical features for water-use efficiency and 2) Physiological adaptations for ion management.
Mangroves are able to maintain high rates of photosynthesis and growth under saline soil conditions because they are able to use water efficiently. The following is a list of structural and anatomical characteristics which confer water-use efficiency amongst mangroves (adapted from Feller and Sitnik 1996; Feller et al. 2010).

1) **Structural and anatomical features for water-use efficiency:**

i. **Modification and arrangement of leaves (Ball et al. 1988; Lovelock et al. 1992):** Mangrove leaves are small with thick waxy coatings. Leaves are positioned on an angle (as opposed to horizontal) which prevents direct sun exposure. These traits help minimize water loss caused by evaporation.

ii. **Salt secreting glands:** Some mangrove species have glands in their leaves which excrete salt. This allows them to maintain lower internal ion concentrations (Hogarth 1999). In some species, salt crystals that are a result of this process can be seen on the surface of leaves.

iii. **Specialized stomatal anatomy (Tomlinson 1986):** Stomata are pores that allow for gas exchange. They provide a similar function as lenticels but occur in a different layer of the plant cell. Because temperature and light intensity is higher on the top surface of leaves due to direct sunlight exposure, stomata occur on the underside of leaves. This prevents excess loss of water vapor while the plant takes in CO₂ during photosynthesis.

iv. **Increased energy allocation to root growth (Ball 1988b; Naidoo 2009):** Plants generally absorb water and nutrients through their roots. Mangroves invest more energy into root production, versus leaf and shoot production, to increase their ability to absorb nutrients and water in surrounding soils.

2) **Physiological adaptations for ion management:**

Mangrove plants are able to tolerate high salinities by actively controlling the concentration of dissolved solutes within tissues (Parida and Jha, 2010). This keeps the plant’s fluids from becoming too diluted or concentrated. Salinity tolerance in mangroves encompasses a range of physiological adaptations for ion management.

i. **Selective accumulation or exclusion of salt ions (Na⁺ and Cl⁻):** Mangroves are able to make osmotic adjustments, resulting in increased water retention and/or Na⁺ and Cl⁻ exclusion in cells (Parida and Das 2005). Because there is typically a higher concentration of dissolved salts in mangrove soils, water has a tendency to remain within the soil. Mangroves selectively accumulate ions in order to overcome this. Consequently water is taken up by the plant roots and unwanted ions and other substances are excluded.

ii. **Ion (Na⁺ and Cl⁻) compartmentalization:** Because Na⁺ and Cl⁻ can be toxic, excess ions are mainly stored in the cell vacuole to maintain cellular concentrations within tolerable limits (Wyn Jones and Gorham 2002). Excess salts can also be transferred to dormant leaves or stored in bark or root tissues (Paridha and Jha 2010).
iii. **Production of high concentrations of compatible solutes:** High concentrations of Na\(^+\) and Cl\(^-\) ions in the cell vacuole must be balanced by other solutes in the cytoplasm; otherwise water can flow from the cytoplasm into the vacuole and damage the cell. In order to achieve osmotic balance, the cell cytoplasm accumulates these other solutes to balance the build-up of salt in the vacuole (Parida and Jha 2010, Parida and Das 2005).

**Adaptations to nutrient limitations**

**Overview**
Mangrove forests are one of the most productive forest types in the world. The nutrients that mangroves require for growth are controlled by several environmental factors which we will explore in a later module. At this point, it is sufficient to understand that mangrove forests are generally very low in nutrients, particularly nitrogen and phosphorus (Reef et al. 2010). In order to survive such limitations, mangrove species have evolved special traits and adaptations that give rise to efficient nutrient use and conservation (Feller et al. 2009). Therefore, an understanding of these traits serves as a platform from which we can explain concepts related to ecosystem productivity, connectedness and food webs - topics which will be covered in later modules.

**Adaptive traits**

*How do mangroves maintain high productivity in nutrient poor environments?*

- **Evergreen:** Mangroves are considered evergreen plants, i.e., plants that keep their leaves throughout the year. This is advantageous as it leads to smaller nutrient investment in new leaves and lower nutrient loss rates due to the long lifespan of leaf tissue (Aerts 1995).

- **High root/shoot biomass ratio:** Mangroves absorb nutrients through their roots. Investing more carbon in root production, relative to shoots, is conducive to nutrient capture in nutrient-poor soils (Komiyama et al. 2008). Both below ground (especially fine roots) and above ground roots contribute to this (Komiyama et al. 2008).

- **Sclerophyllous leaves:** Mangrove leaves are sclerophyllous. Sclerophyll results in thickened, hardened foliage. This property is linked to leaf longevity and nutrient retention (Schlesinger and Hasey 1981) because sclerophyllous leaves take longer to decompose and are subject to lower rates of predation by animals (Coley 1983).

- **Nutrient recycling:** In order to maximize nutrient retention, mangroves are able to resorb nutrients from dying leaves before they age and fall. Although resorption rates vary between species, on average, plants can absorb ~50% of nitrogen and phosphorus from the tissues of dying leaves (Aerts and Chapin 1999).
• High photosynthetic nitrogen-use efficiency (PNUE): PNUE is an indicator of resource-use efficiency (Reef et al. 2010) and can be estimated as the ratio of photosynthetic capacity to leaf nitrogen content (Reef et al. 2010). Mangroves have one of the highest recorded PNUE values among tree types (e.g., Alongi et al. 2005).

• Efficient metabolic processes: Nitrogen is essential for plant growth. Mangroves grow in ammonium rich soils and are uptake ammonium as this requires the least energy investment compared to uptake and assimilation of other forms of nitrogen (Reef et al. 2010, Gutschick 1981).

• Altering rate of growth: An ability to sustain slow growth rates and low nutrient requirements over long periods is an adaptation to nutrient poor environments (Chapin 1980). Mangroves are capable of maintaining very slow growth rates when nutrients are limited and switch to rapid growth when this limitation is lifted (e.g., Feller et al. 2003a, Lovelock et al. 2005, Lovelock et al. 2007a).

Reproduction and dispersal

Overview

Establishing new plants in unstable soils that are regularly submerged by tidal action presents a unique evolutionary challenge. In response, most mangrove species exhibit a specialized strategy for reproduction called vivipary. Vivipary helps mangroves cope with the varying salinities and frequent flooding of the intertidal zone, and increases the likelihood of seedling survival. This form of reproduction has enabled mangroves to survive for thousands of years.

In this section we will briefly explain mangrove pollination and then discuss reproduction and dispersal, focussing on the process of vivipary and its benefits to mangroves as a life history strategy. We conclude this module with seedling mortality. Reproduction, dispersal and seedling mortality can all influence patterns in forest vegetation. Therefore, knowledge of these processes is important for understanding landscape-level patterns in forest structure, a topic which will be covered in the next module.

Pollination in mangroves

Let's first have a quick look at how pollination of mangrove plants occurs:

Mangroves depend on both self- and cross-pollination mechanisms for reproduction (Kathiresan and Bingham 2001). Cross pollination takes place via wind action or animal-plant interactions (e.g., birds, bats and insects). Pollen grains that become attached to animals while they probe flowers for nectar are subsequently deposited on the stigmas of other flowers as the animal moves from mangrove to mangrove. Cross-pollinators vary from one mangrove species to another. For example, Lumnitzera
Laguncularia racemosa is primarily pollinated by birds, while Laguncularia racemosa is pollinated by insects (Tomlinson 1986).

Now that we know how mangroves are pollinated, let’s learn how mangroves reproduce and disperse:

**Mangrove reproduction (Vivipary)**

In most mangroves, germination (the process by which plants emerge from seeds and begin to grow) takes place while the embryo is still attached to the parent tree (NOAA 2010). This type of reproduction is called vivipary and is a unique adaptation to shallow marine environments. The embryos of true viviparous species remain attached to the mother plant for one full year (Bhosale and Mulik 1991). The trees then release the embryos, now called propagules, which are growing plants that are buoyant and able to carry out photosynthesis. While (true) vivipary is rare in terrestrial plants, it is quite common among mangrove genera (Tomlinson 1986, Saenger 2002). Six of the most flood- and salt-tolerant mangrove families display vivipary (Feller et al. 2010).

In a number of other mangrove groups, cryptovivipary occurs. In this form of reproduction, the embryo emerges from the seed coat, but remains hidden within the fruit, prior to dropping from the tree (Farnsworth and Farrant 1998).

As a life history strategy, vivipary increases the chances of successful establishment in an environment where germination of seeds would normally be inhibited (Feller and Sitnik 1996).

**Vivipary provides the following benefits to mangroves** (from Kathiresan and Ajmal Khan 2011):

1) Allows seedlings to develop some salinity tolerance before being released from the parent tree
2) Provides a store of nutrients before the seedling falls from the plant
3) Allows for quick rooting in muddy environments
4) Allows time for the seedling to develop buoyancy

**Propagule dispersal (Hydrochory)**

Most mangroves rely on a process called hydrochory, i.e., where water (mainly tidal action) disperses offspring (propagules) away from the parent tree (Pijl 1973). The propagules do not disperse uniformly (De Ryck et al. 2012) and the distance they travel varies from species to species. For example, Avicennia marina propagules only float for a few days, while propagules of Laguncularia racemosa and Rhizophora harrisonii can remain buoyant for several weeks (Rabinowitz 1978a), therefore the latter of the two species will have offspring that can be expected to settle farther from the parent plant. It is not clear how far propagules may travel but it has been experimentally shown that most Avicennia marina propagules become stranded and establish close to parent plants (Clarke and Myerscough 1991;
Kathiresan and Ramesh 1991) while the extensive range of *Avicennia germinans* throughout the Gulf of Mexico and along the coasts of Central and South America suggests long-distance dispersal (Nettel and Dodd 2007).

The high level of parental investment associated with vivipary and production of fewer and larger propagules enables young mangroves to establish in sediment relatively quickly (Spalding et al. 2010). This type of reproduction is advantageous and important for mangroves because it reduced the chances that young plants become dislodged or uprooted by tidal action before they have a chance to establish (Spalding et al. 2010).

*During growth, dispersal and establishment, mangrove propagules are vulnerable to harsh environmental conditions and predation by animals. Let’s now explore propagule mortality...*

**Propagule mortality**

Propagules may suffer high mortality before they have a chance to settle and establish. Crabs and insects are major consumers of propagules, e.g., crabs can clear almost 100% of propagules in a given area (e.g., Dahdouh-Guebas et al. 1998). Such high levels of predation likely have significant effects on population dynamics and the regeneration of mangroves after a disturbance (Kathiresan and Ajmal Khan 2011).

Mortality is not restricted to propagules. Mangroves are also vulnerable during establishment and early growth. During these periods mangroves may die because of (1) failure to establish while the seed is still able to germinate (2) predation, and (3) dehydration (Farnsworth and Ellison 1991). Following establishment, growth and survival are strongly influenced by physical and chemical stresses. Shading, orientation of the seedling (i.e., upright versus horizontal), flooding and soil fertility can all have significant impacts on the survival of young mangroves (McKee 1995, McGuinness 1996).

**The Mangrove Environment**

**Introduction**

Mangrove forests can form in a variety of different landscapes and within these settings their structure is further modified by spatial patterns in vegetation. In this section we describe the physical environment of the mangrove forest. We identify the conditions which favour establishment, common functional types of forests, patterns in species composition and community structure and some of the major processes which modify these patterns. This section should provide you with a good understanding of landscape-level forest structure and common patterns. Mangroves are found in a variety of tropical and warm temperate coastal settings including river deltas, estuaries, coastal lagoons and open coastlines.
In favourable conditions, mangroves can form extensive forests, with canopy heights exceeding 30 m (Spalding et al. 2010). When conditions are less favourable, i.e., more arid or saline, fewer species survive and those that do form dwarf or scrub formations rarely reaching 3m in height (Spalding et al. 2010).

Mangroves typically thrive in the following environments:

- Sheltered coasts with low wave energy (Kathiresan and Bingham 2001)
- Broad coastal plains where change in elevation is gradual and tidal amplitude is large (Kathiresan and Ajmal Khan 2011)
- Areas where seawater is diluted by regular rainfall, river and groundwater flow (Spalding et al. 2010)

**Functional types of mangrove forests**

Each mangrove forest is unique because their formation and structure is largely dependent on environmental conditions, however some common patterns have been observed.

Early work by Lugo and Snaedaker (1974) described six common functional forest types in the Neotropics. According to their classification, forest formation, structure and behavior are based on the relative influence of tidal or riverine inundation and surface features of the area.

1) **Overwash forest:** Formed through tidal overwash of small, low islands and finger-like projections of larger land masses in shallow bays and estuaries.
2) **Fringe forest:** Occur along the fringes of islands and protected shorelines, these forests are influenced by daily tidal ranges. Exposure on the shoreline makes them vulnerable to erosion, strong winds and turbulent waves.
3) **Riverine forest:** Establish along rivers and creeks and are flooded daily by the tide. Periods of low salinity and upland nutrient runoff makes these systems highly productive causing these floodplain forests to grow very tall.
4) **Basin forest:** Found in inland areas along drainage depressions channeling terrestrial runoff towards the coast.
5) **Scrub (dwarf) forest:** Exist along flat coastal fringes. Individual mangroves are typically <1.5 m tall because this environment tends to be nutrient poor.
6) **Hammock forest:** Similar to basin mangrove forest formation, except that it occurs on ground which is elevated relative to surrounding areas, in contrast to the depressed areas associated with basin forests.
Woodroffe (1992) proposed a more general classification scheme for Old World mangroves, which tend to develop on accreting sediments deposited by rivers and tides.

This scheme distinguishes three types of mangrove forests based on prevailing physical processes:
1. tide-dominated,
2. river-dominated and
3. interior mangrove forests

The New World mangrove forest types described above as classified by Lugo and Snaedaker (1974) can be located within this framework.

**Zonation in mangrove forests**
Within the settings we just described, mangrove vegetation also exhibits vertical and horizontal spatial patterns.
Let's first look at the three major vertical zones, each being characterized by a unique community of organisms (Adapted from Feller and Sitnik 1996):

- **Supratidal:** The area above the high tide. Includes the canopy portions of the trees, and is inhabited by birds, reptiles, crabs, snails, insects and spiders.
- **Intertidal**: Ranges from the high to low tidal height and encompasses the plant’s aerial root systems and peat bank. Organisms inhabiting this zone (e.g., crabs, oysters, barnacles, amphipods, snails, and algae) are subject to periodic submergence.

- **Subtidal**: Occurs below the low water mark where the mangrove roots and peat banks offer substrate for colonization of organisms adapted to constant submergence (e.g., algae, sponges, tunicates, octocorals, anemones, shrimp, polychaetes, brittlestars, jellyfish and seagrasses).

A bird’s-eye view of a mangrove forest sometimes reveals spatial variations in the dominant plant species. These patterns in vegetation structure can be referred to as “zonation”. Let’s explore this concept a little further...

Mangrove forests sometimes form “zones” of vegetation; areas dominated by one or two species. The most widely reported zonation patterns follow changes in elevation, according to species specific tolerances to tidal flooding. In Florida for example, red mangrove trees (*Rhizophora mangle*) usually form monospecific stands along lower intertidal flats, while black mangrove trees (*Avicennia germinans*) grow behind at higher elevations with inundations of less duration (Chapman 1976).

While zonation has been observed in a number of regions (e.g., Papua New Guinea: Ellison 2009; Western Australia: Semeniuk 1980, Florida: Chapman 1976), patterns are rarely consistent from place to place and can vary on local scales (Feller and Sitnik 1996). Several hypotheses have been put forward, but no cause or consistent pattern has been found. Environmental gradients and their effects on tree performance is complex (Ellison et al. 2000) and species may overlap in their range of tolerances to environmental factors (Ball 1988a). Patterns related to flooding tolerance are further influenced by other environmental elements (e.g., salinity).

We explore the factors that affect zonation in the next section.

**Ecological Succession**

Ecological succession is the process of changes in species structure of an ecological community over time. Ecological succession for mangroves is variable (Spalding et al. 2010) and often difficult to detect. We have provided an example that illustrates how in deltas and other coasts which are rapidly growing out into the sea, succession may play a large role in influencing patterns of mangrove forest zonation (Echezuría et al. 2002). However, most coastal intertidal areas are constantly changing and frequently disturbed by altered water flow, storms or erosion. Consequently, mangrove forests are often a patchwork of interrupted succession sequences and clear patterns of succession are difficult to identify (Alongi 2008).

A good example of mangrove forest succession was provided by Echezuría et al. (2002) for an island in the Orinoco Delta, Africa.
Some of the first plants to establish on new sediments were white mangrove (Laguncularia racemosa) and seagrasses.

After 2-3 years, the black mangrove (Avicennia germinans) established under the canopy. The black mangroves eventually grew tall and outcompeted white mangroves for light; effectively shading them out.

The black mangrove trees eventually grew so tall they created an extensive canopy wall. Finally, several species of Rhizophora, a more shade tolerant group, established under the black mangrove canopy.

The idea that mangroves ‘build land’ was put forward in the 1940’s (Davis 1940), but is no longer commonly accepted. Mangroves need pre-existing sediment (soil) to establish, and they colonize intertidal areas where calm conditions permit sediment to accumulate (Perry 2007). However, mangroves do play an important role in trapping suspended sediment (Furukawa et al. 1997, Wolanski 1995, Krauss et al. 2003). The extensive root systems of mangroves trap small clay and silt particles by slowing water movement to speeds which promote settlement (Wolanski 1995, Young and Harvey 1996). Fine roots then bind sediment in the substrate (Alongi 2005). Aerial roots diminish wave energy, which prevents sediments from being washed away and decreases shoreline erosion (Mazda et al. 2007). This is part of a process that allows mangroves to keep pace with rising sea-levels.

Productivity and Biomass

Introduction
Mangroves are highly productive organisms that have a high standing biomass (Alongi 2009). These characteristics are important because they allow mangrove forests to become the rich and diverse ecosystems that they are.

High productivity and high biomass also underpins the importance of mangroves to adjacent ecosystems (Spalding et al. 2010) and the associated species which inhabit them. Furthermore, their high productivity and biomass allow mangroves to play a key role in the global carbon budget and thus in mitigating the effects of climate change.

This topic is so important that it will be discussed in another unit entitled, “Mangroves and Climate Change”. For now, we will learn about productivity and biomass and the difficulties in providing global estimates of mangrove forest production.

Let’s begin this section by reviewing the concepts of ecosystem productivity and biomass.

Ecosystem productivity refers to the rate of generation of biomass within an ecosystem. Biomass is biological material from living, or recently living organisms (BEM 2012). Mangrove trees are the key primary producers within a mangrove forest; they use the sun’s energy and carbon dioxide to create
organic (carbon-based) biological material. Under ideal conditions, mangrove forests are one of the most productive ecosystems on earth, comparable even to the most productive terrestrial forests (Alongi 2009). They also maintain a high standing biomass (Alongi 2009). Altogether, this means that at any given time, mangrove forests are actively creating and storing large amounts of biological material (carbon).

So, where is this biological material located?
Like other plants, mangroves grow by creating and repairing structures such as leaves, branches, stems and roots. However, because mangroves grow in very unstable soils they invest more energy in creating extensive root systems (Spalding et al. 2010).
It has been suggested that they do so to maintain a low ratio of top biomass to root biomass (Komiyama et al. 2000). This helps to maintain stability in soft substrates by providing greater anchorage and lowering the plant’s center of gravity, which allows mangroves to stand upright in soft, wet mud (Komiyama et al. 2008).

Net primary production (NPP) is the gain in organic carbon due to formation of plant tissue. It relates to productivity and biomass and consists of three components: (1) the growth increment (rate of increase in standing biomass), (2) death (including above and below ground litter production) and (3) the rate of grazing by herbivores (Kira and Shidei 1967). The majority of NPP studies have focused on above ground conditions (Komiyama et al. 2008, Spalding et al. 2010). As a result, NPP has generally been underestimated in mangrove forests since above-ground litter production may represent only ∼25–30% of the mangrove forest (Feller et al. 2010). Other aspects of NPP have been scarcely studied, such as below ground litter production and root production (Komiyama et al. 2008). Similarly, little attention has been paid to other primary producers within a mangrove forest, e.g., phytoplankton, benthic bacterial and algal mats. Imported sediments and organic matter may also be a considerable source of organic material, possibly contributing to carbon exports (Alongi 2009, Bouillon et al. 2008).

Measuring Productivity and Biomass –Challenges

Global NPP rates for mangrove forests are difficult to measure because the growth and productivity of a mangrove forest changes in response to a wide range of biotic and abiotic factors, including the dominant species, species-specific traits, local environmental factors (e.g., salinity, light, sediment characteristics), and forest age (Alongi 2011; Komiyama et al. 2008).

Productivity is also variable over large (latitudinal) and smaller (hydrological) scales (Bouillon et al. 2008; Alongi 2009). Recent estimates place global NPP between 140-168 Tg per year (Tg = Teragram, 1 Tg = 1 billion kilograms) (Spalding et al. 2010). This figure is likely conservative (Bouillon et al. 2008) but is comparable to productivity estimates for many terrestrial tropical forests (Alongi 2009).
There is also no consensus on the fate of the organic matter produced by mangroves (Bouillon et al. 2008). However, it has been estimated that ~10% of total NPP gets incorporated into mangrove sediments, ~50% is consumed or decomposed in the mangrove and 30% is exported (the remaining 10% is unaccounted for) (Duarte and Cebrian 1996).

Influences on Ecosystem Structure and Function

Introduction

Residing on the boundary of freshwater, terrestrial and marine ecosystems, mangroves are subject to abiotic (non-living) and biotic (living) influences which affect their structure and function.

These elements interact and affect each other in a complex interplay of processes. Here, we introduce and discuss these elements to help you understand the various forces at work and how the relative influences of each factor shape the mangrove into the incredibly rich and productive environments they are.

We begin this section by first considering relevant abiotic factors.

Abiotic Factors

1) Tidal flooding

Tidal flooding affects mangrove forests in many ways.

i. Zonation: Mangrove species differ in their tolerance to flooding and this is reflected in the general zonation patterns that can be observed.

For example, in south Florida, stands of red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia germinans*) and white mangrove (*Laguncularia racemosa*) grow along a continuum from wettest to driest conditions (Chapman 1976). This occurs because the red mangrove is the most tolerant of flooding and therefore inhabits areas which are flooded a larger percentage of the year (50-70%) (Krauss et al. 2006). In contrast, black and white mangroves are restricted to areas with flooding durations of < 50% of the year (Krauss et al. 2006).

Tidal action may also influence mangrove zonation patterns through hydrochory. That is, propagules may be differentially dispersed due to the physical “sorting out” of species by tidal action (Rabinowitz 1978b).

ii. Forest formation and structure: On both geographic and local scales, tidal flooding has a strong effect on mangrove formation and structure. Broad coastal slopes with large tidal ranges offer a wide band of habitat for mangroves, while steep slopes provide only a narrow band of land for mangrove
establishment and growth (Tomlinson 1986). Trees on the outer edge of the mangrove forest, which are subject to the largest tidal fluctuations, tend to be larger and more productive than trees in the interior forest (Mendelsohn and McKee 2000). Tides also carry saltwater up estuaries against the outflow of freshwater, transporting sediment and nutrients into the mangrove environment and allowing for mangroves to extend inland (Feller and Sitnik 1996).

iii. **Forest productivity:** Nutrient cycling and productivity of mangroves may vary along a tidal hydrology continuum from open to relatively closed wetlands (Gosselink and Turner 1978; Brown et al. 1979; Wharton and Brinson 1979). Among different types of mangroves such as riverine, fringe and basin forests, the flow of nutrients may vary according to tidal influence (Twilley 1988). Organic matter production and export are also affected by tidal flooding (e.g., Odum et al. 1983, Twilley et al. 1986). For example, mangroves exposed to greater tidal activity and water turnover typically have higher litterfall (leaves, twigs, branches and propagules) than mangroves in areas with stagnant water (Pool et al. 1975). Surface litter is less likely to be exported from the mangrove as tidal activity decreases (Twilley 1985), thus wetlands that are infrequently flooded may have less nutrient mobilization and export (Brinson 1977, Schlesinger 1978, Brinson et al. 1980).

2) **Freshwater**

Freshwater plays a role in determining mangrove biomass and species distribution (Kathiresan and Ajmal Khan 2011), both through direct effects and because it moderates other soil properties (such as salinity). On a geographic scale, areas of higher coastal rainfall and high riverine inputs of freshwater typically support more diverse mangrove communities compared to areas of low coastal rainfall and limited runoff (Duke et al. 1998). High rainfall may encourage mangrove growth and expansion. For example, along the southern coast of Costa Rica, where annual rainfall is very high, mangroves exceed 35 m in height (Jiménez 1990). Similarly, mangroves in Indonesia have high biodiversity and luxuriant growth, attributed to high humidity and rainfall (Kathiresan and Ajmal Khan 2011). In contrast, in areas of low precipitation, high salinity, and low nutrients such as in the Sudan and Ethiopia, mangrove forests are mostly monospecific and bushy (Kathiresan and Ajmal Khan 2011).

3) **Sunlight**

Mangroves need sunlight for photosynthesis. Although mangroves occur in tropical habitats where they are exposed to high light intensities, photosynthesis in mangrove cells piques at low light levels (Kathiresan and Bingham 2001). Strong sunlight can reduce mangrove photosynthesis (Cheeseman et al. 1991) while extensive shading can also have negative effects. Seedlings that grow under a closed canopy exhibit reduced growth and survival rates (Clarke and Allaway 1993, Ellison and Farnsworth 1993, Koch and Snedaker 1997, Sherman et al. 2000) while gaps in the canopy can promote rapid growth of previously shaded trees (Kathiresan and Bingham 2001). Shade tolerance differs among mangrove species and may change according to the plant’s developmental stage.
For example, red mangroves exhibit properties of both a “light demanding” and “shade tolerant” species. In contrast to other species, *R. mangle* can grow in the shaded mangrove understory at low growth rates, and also grow rapidly when canopy gaps form (Ellison and Farnsworth 1993).

4) **Salinity**
Salinity is a major factor which regulates mangrove forest structure and productivity (e.g., Imbert et al. 2000). Salinity levels in a mangrove environment can range from almost freshwater to nearly three times the salinity of sea water (Cintrón et al. 1978). In some locations, distribution of mangrove species may follow a pattern of zonation according to respective salinity tolerances (e.g., Imbert et al. 2000). To what extent these differences are responsible for mangrove distribution is not fully understood. It is likely that the physiological stresses associated with salinity, or the combination of salinity and other co-varying soil factors, control forest structure and growth along tidal gradients (Sherman et al. 2003).

5) **Sediment characteristics**
Although mangrove plants can grow in a range of sediment types, they tend to thrive in fine-textured loose mud or silt. Near coastal reefs and oceanic islands, mangroves grow on peat, i.e., decayed vegetation (Parkinson et al. 1994, Cameron and Palmer 1995). Here, we discuss some sediment characteristics and their effects on mangrove growth and productivity.

i. **Waterlogging and soil redox potential**
Waterlogged soils are typically anoxic. As described earlier, mangroves are able to transport oxygen to the area directly adjacent to roots through a process called radial oxygen loss (ROL) (Armstrong, 1979). Mangrove soils tend to be moderate to strongly reducing (Thibodeau and Nickerson 1986, McKee et al. 1988). This is important because the reduction of compounds can stabilize heavy metal soil contaminants, like Lead (Pb) and Zinc (Zn). This process underlies the biofiltration function of mangroves; it is part of the process which enables them to remove harmful pollutants from soils. This process also influences whether nutrients are available for plant uptake and subsequently, plant growth (Reef et al. 2010).

ii. **Soil pH**
*pH* is a measure of how acidic or basic a substance is. The *pH* of soil influences plant growth because it affects nutrient availability, e.g., essential elements such as phosphorus (Black 1993, Slattery et al. 1999). Most mangrove soils have a *pH* range of 6-7, but some have a *pH* as low as 5 (Kathiresan and Ajmal Khan 2011). Soil *pH* is modified by the decomposition of leaf litter and tidal currents (Tam and Wong 1998).

iii. **Nutrient availability**
Nutrient availability influences mangrove primary productivity - the process through which plants synthesize new organic matter. Most mangrove soils are nutrient poor (Lovelock et al. 2005), but this
varies greatly within and between ecosystems (Feller et al. 2003b). For example, nutrient concentrations tend to be extremely low in oceanic settings and very high in muddy systems with frequent sediment deposition and external enrichment (Alongi 2009).

Mangroves are very sensitive to changes in nutrient availability (Feller et al. 2009, Lovelock et al. 2007b, Naidoo 2009, Boto et al. 1985, Naidoo 2006, Yates et al. 2002), particularly, nitrogen and phosphorus, as these elements have a strong impact on plant growth (Krauss et al. 2008). Mangrove responses to nutrients are complex (Schaffelke et al. 2005). Typically, nutrients enhance growth, but excess nutrients can lead to plant death. There are also species specific responses to nutrient enrichment. For example, in a field experiment in Florida, nitrogen fertilization led to an increase in photosynthesis in black mangroves while white mangroves showed no response (Lovelock and Feller 2003). Overall, long-term excess of nutrients is typically associated with tree mortality and reduced resilience (Lovelock et al. 2009). This last point is important because globally, many mangrove forests are threatened by excess input of nutrients.

iv. Sulphide concentration
The presence of sulphide is a characteristic feature of mangrove soils. In general, high sulphide levels can damage, reduce growth, and kill mangroves (Youssef and Saenger 1998). Sulphide may have a large influence on distribution (Nickerson and Thibodeau 1985, McKee et al. 1988, McKee 1993, Youssef and Saenger 1998). For example, in a Bahamian mangle, the distribution of both red and black mangrove trees has been correlated with soil sulphide concentration (Nickerson and Thibodeau 1985).

As previously discussed, mangroves can move oxygen to the rhizosphere via radial oxygen loss. This process inhibits the buildup of sulphate in the rhizosphere. Species may vary in their ability to oxidize soils, themselves moderating the concentration of soil sulphide (McKee 1993). This is an area of research still being explored.

Biotic Factors
Now that we understand the effects of some abiotic factors, let’s turn our attention to the influence of biotic factors on the structure and function of mangrove ecosystems.

The impact of biotic factors on mangrove ecosystems has only been recognized during the last twenty years (for review, see Cannicci et al. 2008). That is, the significance of crabs as ecosystem engineers in a mangrove forest, along with other invertebrates has come to light.

1) Crabs
Crabs are considered a main actor in forest structuring processes and are often considered “ecosystem engineers” in the mangrove.

i. Damage by herbivorous crabs: Although the majority of leaf-eating crabs consume dead leaf litter, some species of tree-climbing crabs feed on fresh mangrove leaves (Fratini et al. 2005). One such
species, *Aratus pisonii*, can damage up to 40% of the leaves on a single red mangrove tree, which can have a considerable negative impact on tree growth (Beever et al. 1979, Erickson et al. 2003).

**ii. Retention of mangrove production within the ecosystem:** Crabs play a significant role in retaining and reducing the export of organic matter from the mangrove through the consumption and burial of leaf litter (see Lee 1989, Robertson and Daniel 1989, Emmerson and McGwynne 1992). This is important for preserving nutrients and energy in a nutrient-poor ecosystem like the mangrove (Nordhaus et al. 2006). For example, in Old World mangroves, crabs can consume up to 100% of the annual litter fall in mangrove forests (Cannicci et al. 2008).

**iii. Enrichment of mangrove organic production:** Leaf-eating crabs enhance mangrove primary production by returning litter to the system as finely shredded, partially digested fecal material (Lee 1997). Approximately 60% of the material consumed by crabs is eliminated as feces (Lee 1993). This material is then easily consumed by detritivores; organisms that feed on small particles of dead matter and organic waste. The passage through the gut of the crab can enrich the raw mangrove matter with carbon and nitrogen, and bacterial biomass (Nordhaus and Wolff 2007). Consequently, litter digestion greatly enhances the decomposition of mangrove leaf litter and accelerates nutrient cycling within mangrove ecosystems (Robertson and Daniel 1989).

**iv. Reduced competition among young trees by propagules predation:** Crabs consume large amounts of young mangrove propagules. In reducing overall numbers of plants, they can reduce the amount of competition between plant species for resources. Consequently, crab predation on mangrove seeds may be one factor which influences species distribution (See Smith 1992; Allen et al. 2003 for reviews).

**v. Bioturbation and consequent ecosystem engineering:** Burrowing by crabs causes bioturbation; stirring and mixing of the soil. This allows oxygen to reach the soil sediments, which decreases sulphide concentrations in mangrove soil and benefits mangrove productivity (Cannicci et al. 2008). Through their digging activity, crabs also increase water exchange between sediment grains, which can enhance removal of phytotoxins (Howes and Goehringer 1994). Crab burrows also positively affect water in the soil. Burrows allow for the exchange of water between swamp soil and the overlying water (Ridd 1996), which helps remove accumulated salt from around mangrove roots (Stieglitz et al. 2000).

*Crabs are clearly important ecosystem engineers within the mangrove system; however they are not alone in this capacity. Let’s now explore some of the other important animal groups which influence mangrove structure and function:*

**2) Mollusks and other marine taxa**

Mollusks are abundant in mangrove forests (Plaziat 1984). Some, particularly, mud whelks (marine snails), can consume significant amounts of fallen leaves, contributing to leaf decomposition (Fratini et al. 2004, Slim et al. 1997). They also feed on mangrove propagules and therefore can influence mangrove restoration and regeneration (Plaziat 1984, Dahdouh-Guebas 2001, Dahdouh-Guebas et al. 1998). In addition, they can modify the biological, chemical, and physical properties of the soil surface through their movement, e.g., leaving tracks and destabilizing the sediments (Carlen and Olafsson 2002).
Sponge, oyster and barnacle communities on mangrove roots and trunks can also have strong impacts on mangroves. For example, some sponges can induce the formation of rootlets, indirectly increasing mangrove nitrogen uptake and encouraging growth (Ellison et al. 1996). On the other hand, heavy growth of barnacles and oysters on roots can also hamper root growth (Perry 1988).

3) Insects
Leaf eating, wood boring and flower/fruit/seed-feeding species of insects can strongly impact mangrove growth and reproductive success. Trees can lose up to almost 40% of their leaves due to insect predation (Burrows 2003) and insects also feed on young propagules. When plant resources are reallocated to compensate for herbivore damage, can lead to a decrease in reproductive output (Anderson and Lee 1995, Cannicci et al. 2008, Tong et al. 2003).

Ecosystem Dynamics (mangrove food webs)

Introduction
Species diversity in a mangrove forest stems from the spectrum of habitats created and modified by mangrove plants (Feller et. al. 2010). Thousands of species of bacteria, plants and fungi are linked to mangroves. Together, they make up a complex community characterized by numerous interdependencies, patterns of predation, parasitism and commensalism (Spalding et al. 2010). The degree to which different species depend on the mangrove environment is highly variable. Some species are completely restricted to mangrove environments, while others are opportunists primarily found elsewhere but sometimes benefiting from mangroves. For other species, dependence on mangrove environments varies according to life history stage.

In this section we first describe the mangrove as a habitat, then we briefly consider the range of functional roles played by species in typical mangrove ecosystems and finally, we introduce and describe a typical mangrove food web.

The Mangrove Habitat
The physical structure of a mangrove forest serves as a foundation for many ecological interactions. Similar to terrestrial trees, mangroves have a woody trunk and a leafy canopy. Their unique aerial root system forms an extensive aboveground structure which increases forest complexity. These structures provide habitat for supratidal and intertidal communities (Feller et al. 2010). Additionally, roots suspend into the water column where they provide food and shelter for shrimp, fish and other free swimming creatures (Nagelkerken et al. 2008). Because mangroves are typically mud- or peat-based systems, in intertidal areas prop roots are the only solid surfaces available. As such, they provide hard surfaces essential for attachment by sessile (non-mobile) marine organisms (Feller et al. 2010).
**The Mangrove Community**
The mangrove community is made up of four key players, as shown. Each has its own unique role within a mangrove.

1) **Primary producers:** Mangrove plants are the key primary producers within a mangrove forest, but are not alone in this role. Mangrove associated primary producers include phytoplankton, benthic bacterial and algal mats as well as algal communities which colonize the roots (Feller et al. 2010). Algae in particular are highly productive and due to their simple body structure are more readily available as food for plants (Spalding et al. 2010).

2) **Detritivores:** A major part of the mangrove food web is driven by detritus (Odum and Heald 1975). Detritivores are organisms that feed on dead matter and organic waste. Mangrove derived detritus such as fallen leaves, propagules and flowers are an important food source for many invertebrates such as crabs and gastropods (Camilleri 1992). Crabs play an important role in reducing nutrient loss from mangroves by ingesting fallen leaves and also by transporting leaf litter into their burrows (Alongi 2009). Other notable detritivores include soil microbes, which are critical to nutrient cycling and benthic associated meiofauna such as copepods, flatworms and nematodes (Nagelkerken et al. 2008).

3) **Herbivores:** Herbivores play an important role in increasing habitat and community complexity in mangrove forests (Feller 2002). Mangrove plants are attacked by wood-feeders which prune trees and can cause significant structural damage (Feller 2002). A broad range of herbivorous species, from smaller insects, crabs and mollusks, to larger rodents and monkeys, can be seen in mangrove forests. Such herbivores create light gaps in the canopy, decrease primary production, interfere with internal nutrient cycling, and increase nutrient loss (Feller 2002). Nevertheless, leaf-feeding is difficult as mangrove leaves are protected by thick, waxy cuticles and tannins (a bitter plant compound) (Cundell et al. 1979) which may deter herbivores (Kathiresan 1992).

4) **Predators:** Predators play an important role in mangrove food webs at every scale (Spalding et al. 2010). Although the tiger and estuarine crocodile are two prominent examples, predation by crabs, prawns and birds are also integral components of mangrove ecosystem dynamics.

**Mangrove Food Web**
Now that you understand the different functional roles of animals within mangrove ecosystems, let’s look at how a typical mangrove food web operates (see image below).
Mangrove forests are unique habitats for a large variety of flora and fauna. Birds and monkeys occupy the canopy, shellfish attach themselves to roots, and snakes and crocodiles use the forest as nesting and hunting grounds. Mangroves also provide valuable nursery habitat, including food and shelter, for many fish and crustacean species.

A major part of the mangrove food web is driven by detritus (Odum and Heald 1975, Spalding et al. 2010), which consists of small particles of dead plants and animals, as well as bacteria. A typical detritus-based food web in the mangrove can be described as follows. Mangrove litter, which includes leaves, branches, propagules, and fruit, falls from the tree. Some of this litter is consumed directly by crabs and marine snails, but the majority is broken down to detritus before being consumed by other organisms. Bacteria and fungi are the first to break down the litter, enriching it with nutrients and protein, creating food for crustaceans and mollusks.

Crustaceans and mollusks further decompose the litter, producing waste in the process. This waste, along with even smaller particles of mangrove litter, is eaten by fish and other crustaceans. In turn, these animals are eaten by larger consumers, such as pelicans and crocodiles. During decomposition, dissolved nutrients and carbon are released into water.

While some nutrients are incorporated into sediments within the mangrove, a portion are also transported out of the mangrove, potentially supporting adjacent habitats (Alongi 1990, Robertson et al.)
Mangroves are tightly connected to adjacent habitats through the movement of species and water as well as dissolved carbon and nutrients.
1.5 Connectivity to Adjacent Ecosystems

**Overview**

Inhabiting the interface between the land and sea, mangrove forests are closely linked to upstream freshwater, terrestrial and offshore marine ecosystems through the movement of organisms and water, as well as carbon and nutrients. This unique connectivity contributes to their economic value, but also increases their vulnerability to human and natural disturbances.

The following is a list of some of the common ecosystems that can be found adjacent and linked to mangrove habitats (adapted from Spalding et al. 2010).

**Saltmarshes**

Saline wetlands dominated by grasses, herbs and low shrubs. Commonly found throughout the tropics, particularly in more arid locations. There are not always distinct boundaries between mangroves and saltmarshes. They differ from mangrove forests mainly in the height of mangrove trees that dominate.

**Salt pans/flats**

Areas of such high aridity and salinity that little if no vegetation is able to survive. They occur in highest intertidal areas with highly saline groundwater due to infrequent flooding, low rainfall and high evaporation rates.

**Swamp forests**

Exist in upper intertidal areas in mostly humid regions. They tend to be palm dominated in West and Central Africa and peat dominated in South East Asia.

**Tidal freshwater forests**

Associated with larger estuarine systems which have high freshwater input. They are characterized by low salinity and high in materials, e.g., clay, silt and fine organic matter, derived from upriver and terrestrial sources.

**Mud flats/Tidal flats**

Occur offshore below mid-tide level and are considered unvegetated but productive systems. They are important feeding ground for birds, fish and crustaceans.

**Seagrasses**
Flowering plants that grow in marine, fully saline environments. Like mangroves, they are important for binding and trapping marine sediment. They are common in marine waters neighbouring mangroves, and are home to many mangrove associated species.

Coral reefs

Associated with coasts and islands where nutrient input is low. They shelter coasts from wave action, allowing mangroves to thrive. Many reef organisms have close ecological links to mangroves.

Connectivity to surrounding environments

Connectivity to terrestrial and marine ecosystems underlies the role that mangroves play in coastal protection.

Being situated on the edge of the land and sea, mangrove forests act as a physical barrier to wave energy, and their extensive root systems bind and stabilize sediment (Furukawa et al. 1997, Wolanski 1995, Krauss et al. 2003). Because of these properties, mangrove forests can reduce erosion rates and attenuate wave action (Mazda et al. 2007), preserving the integrity of the land while protecting coastal communities within and behind them. Although mangrove forests are not immune to erosion or the effects of storms, they do provide a stable barrier which can buffer their effects. In this way, mangroves also protect many terrestrial ecosystems.

An understanding of connectivity is important because disruption of the link between mangroves and other environments can have very negative consequences (Feller et al. 2010). For example, continual mangrove clearing for shrimp aquaculture over a 20 year period in the Philippines resulted in a 90% drop in offshore fisheries production (Primavera 1997). Thus, the loss of mangrove forests not only has direct impacts on ecosystem services, but can compromise the functionality of adjacent ecosystems (Feller et al. 2010).

Connectivity to Freshwater Environments

The connectivity of mangroves to freshwater environments contributes to the natural biofiltration services which mangroves provide (Feller et al. 2010). Often, terrestrial watersheds are subject to various sources of pollution which can lead to eutrophication (nutrient enrichment). The structural complexity of mangroves allows them to constrain water and trap sediments (Spalding et al. 2010). Their high productivity enables them to metabolize excess nutrients and store organic matter (Alongi and McKinnon 2005). Situated between the land and sea, mangroves act as a natural biofilter and intercept land-derived nutrients, pollutants, and suspended matter before such contaminants reach coastal environments (Rivera-Monroy and Twilley 1996, Tam and Wong 1999). This ability has been evaluated as a potential solution for the treatment of aquaculture and sewage effluent (e.g., Gautier et al. 2001, Vaiphasa et al. 2007).

Connectivity to Terrestrial Environments
Mangrove habitats are connected to terrestrial environments and associated fauna, however, this connectivity is not well understood (Feller et al. 2010). We know that mangroves provide an important interface where marine and terrestrial food webs overlap and organisms interact to gain access to food or shelter, or serve as a nesting or resting ground (Nagelkerken et al. 2008). For example, the estuarine crocodile (*Crocodylus porosus*) may feed on land-dwelling mammals which visit mangrove banks for food or water. In northern Kenya elephants visit the large stands of *Heriteria littoralis* in the Tana Delta to forage on associated plants such as dwarf palm, *Hyphaene coriacea*, within the mangrove forest (Samoilys et al. 2011a).

**Connectivity to Marine Environments**

Mangroves are connected to marine environments through movement of water across ecosystem boundaries and through movement of fauna. As such they play an important functional role in these adjacent marine ecosystems. The most commonly cited are their role as nursery areas for many marine fishery species (vertebrate and invertebrate) and the supply of nutrients which enhance the productivity of neighbouring ecosystems (Kristensen et al. 2008; Nagelkerken et al. 2008). The productivity of mangrove forests can be equivalent to the most productive terrestrial forests, although it is highly variable (Bouillon et al. 2008, Alongi 2009). This productivity which is in part provided by epiphytic algal communities living on mangroves, is important for adjacent coastal food webs thereby enhancing the productivity of neighbouring habitats through “outwelling” of nutrients (Alongi 2009). Disruption of this nutrient supply, for example through clearing of mangroves, can therefore have profound impacts on neighbouring marine habitats.

Mangroves serve as critical intertidal habitats for many marine species. They provide nursery habitat for fish and prawns species, offering food, shelter and protection to juveniles and adults, many of commercial value (Nagelkerken et al. 2000, Sheaves 2005, Robertson and Duke 1990). There is a strong relationship between the presence of mangrove habitat and fish catch (Lee 2004, Manson et al. 2005a, Meynecke et al. 2007). For example, the biomass of several commercially important coral reef species are known to double when adult habitat is connected to mangroves (Mumby et al. 2004). In Queensland, Australia, mangroves and associated habitats are believed to support approximately 75% of commercial fisheries (Manson et al. 2005a). Offshore prawn catch (particularly banana prawns) in this region has been correlated with extent of mangrove coverage (Manson et al. 2005b, Meynecke et al. 2008). Although mature prawns are captured offshore, many commercial species spend their early life stages in mangrove habitats (Dall et al. 1990).

The fish and prawn species which primarily contribute to this relationship are dependent on bays and estuaries for at least part of their life cycle (Cappo et al. 1998, Nagelkerken and van der Velde 2002). Adults of these species typically spawn offshore, producing eggs that disperse in the water column. These eggs develop into planktonic larvae which swim, or are carried by currents, into inshore and estuarine waters where mangroves and other habitats (e.g., seagrass and algal beds) occur (Nagelkerken et al. 2008). For example the highest juvenile fish abundances of the coral reef species *Haemulon*
flavolineatum in the Caribbean are found in mangrove/seagrass nurseries where predation risk is lower, though growth rate is also lower, suggesting predator avoidance is the critical factor (Grol et al. 2008). Juveniles or adults migrate out of the estuary or lagoon, and back towards offshore areas such as coral reefs (Nagelkerken et al. 2008). Under this life history scenario, mangroves provide an important link in the chain of habitats required by different species during their life cycles.

Most marine fishes and invertebrates use more than one habitat during their lives, including the gray snapper (Lutjanus griseus): open water, mangroves, sea grass, and coral reef are important for growth and survival during different life stages.

While the nursery habitat role that mangroves play seems clear, the potential export of nutrients and detritus to connected coastal systems is less understood. Export of detritus, mangrove litter and nutrients to offshore consumers, termed “outwelling” was traditionally considered a critical functional role of mangroves as well as an argument for their conservation (see “outwelling hypothesis”) (e.g., Snedaker 1978). However, this view may be overly simplistic (Kneib 1997) and recent studies suggest that outwelling may be less significant than previously thought (Lee 1995). The large flux of mangrove detritus to the coastal ocean has been shown to have recognisable effects on aquatic food webs in some areas (Alongi et al., 1989, Alongi 1990), but nutrient enhancement from export of mangrove litter appears to be insignificant, as demonstrated in Gazi Bay, Kenya (Hemminga et al. 1994) However, work on outwelling is still largely limited to localised studies with only one continental scale study by Dittmar et al. (2006) which showed that a significant fraction of the net carbon fixation through primary production from mangrove forests is exported to coastal waters as DOC (Dissolved Organic Carbon).

Furthermore, studies indicate that offshore fisheries may not be driven by the outwelling of nutrients from estuaries (Loneragan et al. 1997, Chong et al. 2001) and that nutrients may only directly contribute to food webs within highly restricted areas (Loneragan et al. 1997). Mangroves may contribute
substantial amounts (up to 57%) of organic matter to sessile, reef forming invertebrates (Granek et al. 2009); however, the question remains whether mangrove-derived nutrients provide essential nutrients or minerals that would be limiting if they were to become unavailable (Granek et al. 2009). Nevertheless, mangroves probably contribute >10% of the terrestrially derived DOC transported to the ocean while they cover only <0.1% of the continents’ surface. Further, organic carbon export from mangrove areas to the ocean is more than one order of magnitude higher in proportion to their net-primary production than any major river (Kristensen et al 2008).
2.0 Biodiversity in the Mangrove

2.1 Fish and Fisheries

Introduction – fish in mangrove forests
Fish inhabit the creeks, pools and inlets of the mangrove forest. Fish in mangroves can be classified as the following (Robertson and Duke 1990):

- **Permanent residents**: Spend their entire life cycle in the mangroves
- **Temporary long-term residents**: Associated with mangroves for at least one stage in their life cycle
- **Temporary short-term residents**: Sporadic users of the mangroves

Fish are important consumers within the mangrove ecosystem, feeding on crustaceans, nematodes, mollusks, insects, detritus, planktonic larvae and other fish (Sasekumar et al. 1992). In turn, fish are consumed by a variety of higher predators both within the mangroves and in adjacent habitats and provide important sources of nutrition and economic income for many people worldwide.

Mangroves as habitats for fish
The mangrove prop roots, pneumatophores, fallen leaves and branches make a complex habitat for many prey organisms of fish. This habitat complexity also provides shelter for fish from their predators. High rates of primary productivity also make the mangrove a rich source of nutrients (Spalding et al. 2010). Many fish species found within mangroves also occur in adjacent habitats such as seagrass beds or coral reefs. These non-resident species may use mangroves for either feeding or shelter on a daily basis (De Troch et al 1996). For example, on Caribbean islands, reef fish may use the mangrove as shelter during the day and migrate to seagrass beds at night to feed (Nagelkerken and van der Velde 2004). Mangroves also provide an important foraging habitat for fish at high tide (Nagelkerken et al. 2008).

Mangroves as nurseries for fish
Juvenile fish are often found in higher densities and with greater rates of survival, within mangroves compared to offshore habitats, where they live as adults (Nagelkerken 2009). These features suggest that mangroves act as important nursery areas that contribute to adult populations (Nagelkerken 2009). Mangroves are attractive habitats for fish, particularly juveniles, for three potential reasons (reviewed in Nagelkerken et al. 2008):

A) **Reduced predation**: Juvenile fish in the mangroves may suffer less predation. This may be because the turbid waters reduce the effectiveness of large visual predators (Blaber and Blaber 1980, Cyrus and Blaber 1987), shallow waters exclude large fish (Shulman 1985) and the high structural complexity of the mangrove enables small fish to hide from predators (Laegdsgaard and Johnson 2001).
B) **Increased food supply:** Mangroves provide more and diverse food sources for juvenile fish (Blaber 1980, 1987, Robertson and Duke 1987, 1990b). Sheltered mangroves provide detritus, microfauna and flora which are unavailable in offshore waters. Additionally, most juvenile fish which occur in mangroves consume zooplankton (Robertson and Duke 1987, Chew et al. 2007) and zooplankton abundance within mangroves can be much higher than in adjacent coastal waters (Robertson et al. 1988).

C) **Increased shelter or living space:** The habitat created by mangrove roots is important for a wide variety of fishes. Mangrove pneumatophores and prop roots create structural complexity and shade. The fish species composition of mangroves varies according to species of mangrove tree and substrate type - hard or soft (Nagelkerken et al. 2008).

**Mangroves – important habitats for critical life history stages**

Fish often migrate between ecosystems to live out their different life stages (e.g., egg, larvae, juvenile and adults) (Bosire et al. 2012). This may occur because each life stage requires distinct resources and involves different ecological processes (Bosire et al. 2012). For example, in Australia, the mangrove red snapper (*Lutjanus argentimaculatus* – also known as the “mangrove jack” in Australia) lives in freshwater habitats as juveniles and moves to mangroves as young adults (Connolly et al. 2005). As the young adults develop and migrate offshore, they live in deep inter-reef habitats, before arriving at coral reefs. This species lives and reproduces on reefs as adults (Connolly et al. 2005).

Many coral reef fish utilize mangroves as nurseries during their juvenile phase and then migrate seaward to their adult reef habitat (Sheaves 1995, Nagelkerken et al. 2000). Adults usually spawn offshore on the reef –producing pelagic larvae (Nagelkerken et al. 2008). These larvae swim, or are carried by currents, into inshore and estuarine waters where mangroves and other habitats (e.g., seagrass and algal beds) occur (Nagelkerken et al. 2008). Following juvenile development, these fish then migrate seaward to their adult reef habitat. In this way, mangroves act as important nursery sites for reef fish.

**Mangroves and reef fish communities**

Studies from the Caribbean indicate that the presence of mangroves can strongly influence fish community structure on neighboring coral reefs (Mumby et al. 2004, Nagelkerken et al. 2000, Dorenbosch et al. 2006). An important study by Mumby et al. (2004) showed that extensive mangrove habitats can enhance the biomass of fishes on adjacent reefs. The authors determined that the biomass of several commercially important reef fish species more than doubled when adult habitat was connected to mangroves. Another study showed that on islands without mangroves and seagrass beds, fish on adjacent reefs are either absent or present in much lower densities than on islands with these nursery habitats (Nagelkerken et al. 2002). There is also growing support for a nursery role of Indo-Pacific mangroves in replenishing certain reef fish populations (e.g., Kimirei et al. 2013).
Mangroves and reef resilience
Mangroves may enhance the resilience of coral reef populations to disturbance, by supporting populations of herbivorous fish (Mumby and Hastings 2008). On coral reefs, macroalgae compete with corals for space (McCook et al. 2001). During a disturbance, coral is killed or removed, and space is created. After disturbance, if algae are not kept in check, it may outcompete corals for space and cause a shift from reefs dominated by coral, to reefs dominated by algae. Grazing reef fish (among other herbivores) eat algae and thus control their populations. After a disturbance, herbivorous reef fish are critical to preventing a shift from coral-dominated to algae-dominated reefs. *For a review of coral–algal phase shifts on coral reefs see McManus and Polsenberg (2004)*

Mangroves and nearshore fisheries
A large number of vertebrate and invertebrate species are harvested in mangroves and nearshore areas by subsistence and artisanal fishers around the world (Waycott et al. 2011). Although the role of mangroves in supporting nearshore fisheries productivity is not completely understood, it is widely appreciated (Bosire et al. 2012). The fisheries value of mangroves depends on a range of factors that include the species being considered, site characteristics, climatic variability, and presence, abundance, and movements of competitors and predators (Faunce and Serafy 2006, Aburto-Oropeza et al. 2008). For successful integrated management of mangroves, an understanding of the complexity of factors that give rise to productive and diverse fisheries is vital.

Harvesting from mangrove areas can be divided into: a) capture of resident species such as arc shells (*Anadara* spp.), mangrove crabs (*Scylla* spp.) and oysters and b) capture of fish and prawns that use mangroves temporarily during high tide for feeding (Waycott et al. 2011). In Eastern Africa these fisheries in mangrove intertidal areas typically use fence traps, handlines and a range of nets from circular seines to small gill nets (Samoilys et al 2011b).

Several studies have found correlations between mangrove area, or extent and nearby fish catch (Manson et al. 2005b, Paw and Chua 1991, de Graaf and Xuan 1998). For example, in the Gulf of California, mangrove-associated fish and crab species account for 32% of small-scale fisheries landings in the region (Aburto-Oropeza et al. 2008). Similarly, approximately 75% of commercial fish species caught in the West African Marine Eco Region depend on mangroves for reproduction and as nurseries for their young (USAID 2009). As discussed earlier in the section on connectivity with adjacent ecosystems several commercial reef fish species depend on mangroves for their juvenile stage (Nagelkerken et al. 2008). While the relationship between mangroves and nearshore fisheries production seems to be specific to the physical characteristics of the mangroves and biological characteristics of adjacent offshore areas, loss of mangroves is likely contributing to declining catches in coastal fisheries (Clough 2013).
Other mangrove fish

- Mudskippers
  In the Indo-Pacific, mudskippers are a charismatic fish commonly found in mangroves and exposed mud flats. These are completely amphibious fish which use their fins to walk on land. They have several adaptations to maintain their amphibious lifestyle, including:
  - Using their pectoral fins to “skip” on land (Harris 1960)
  - Breathing through their skin and the lining of their mouths (Graham 1997)
  - Digging deep burrows in the sediment that allow them to control their body temperature (Tytler and Vaughan 1983) and escape marine predators during high tide (Sasekumar et al. 1984)

- Ornamental Fish
  While most ornamental fish are associated with coral reefs, a relatively high number are also associated with mangroves and mudflats (Mandal et al. 2012). Typically, the ornamental species in mangroves are of estuarine origin, but some are also marine (Mandal et al. 2012). Popular ornamental fish found in the mangroves include “scats”, archerfish, “monos” and others. The lined seahorse (*Hippocampus erectus*), which can be found in association with mangrove roots, is frequently harvested for the aquarium trade (Dias et al. 2002).

- Elasmobranches (sharks, rays and skates)
  Many species of sharks and rays occur in mangrove environments (Matthes and Kapetsky 1988). Juvenile lemon (Morrissey and Gruber 1993, Wetherbee et al. 2007) and blacktip reef sharks (Chin et al. 2012), smalltooth sawfish (Simpfendorfer et al. 2010) and giant shovelnose rays (White and Potter 2004) have all been found in association with mangroves. It is widely known that many elasmobranches may use nearshore habitats as nursery areas (Nagelkerken et al. 2008). As a habitat, the mangrove offers a number of prey items and also the complex structure provides refuge from predators which may be a threat (Morrissey and Gruber 1993).
2.2 Flora and Fauna in the Mangrove

2.2.1 Mangrove Flora

In general, mangrove species have been categorized into two groups: true mangroves and mangrove associates (Selvam et al. 2004, Wang et al. 2010). True mangrove plants are species which have adapted to tropical intertidal environments and are seldom, if ever, found elsewhere (Spalding et al. 2010). Plants that grow in other coastal environments, and also within mangroves are considered to be mangrove associates (Baba et al. 2013).

True mangrove species

True mangrove plants are the major constituents of the ecosystem; it is their presence that creates and defines the mangrove environment (Jayatissa et al. 2002). These are species which are limited, or “exclusive” to the mangrove environment (Selvam et al. 2004). This is in contrast to mangrove associates, which are mainly distributed in a terrestrial or aquatic habitat, but also occur in the mangrove ecosystem (and are, therefore, not ‘exclusive’ to it) (Tomlinson 1986, Lacerda et al. 2002). While mangrove trees are the predominant vegetation in most areas, mangrove plants also include ferns, several shrubs and a palm (Spalding et al. 2010). True mangroves do not belong to a single genetic group; rather they are an assemblage of plants which share certain adaptations to life in the intertidal zone (Clough 2013).

True mangrove plants have been identified as those which possess most or all of the following traits (Tomlinson 1986):

- They grow only in the mangrove environment and do not extend into terrestrial plant communities
- They play a major role in determining the structure of the plant community and have the ability to form pure stands
- They have morphological specializations to live in waterlogged environments – e.g., aerial roots and specialized mechanisms of gas exchange
- They possess physiological mechanisms for salt exclusion and/or excretion
- They have viviparous reproduction
- They are taxonomically isolated from terrestrial relatives.

True mangroves are foundation species

In contrast to other forest types, mangrove forests consist of relatively few species (Duke et al. 1998). In the most diverse sites, 30-40 species can be present; however in many places only one or a few occur (Duke et al. 1998). Regardless, these few species are the foundation of incredible and complex ecosystems. The structure they provide defines communities by creating habitats and locally stable conditions required by other species (Feller et al. 2010, Ellison et al. 2005). They also modify non-living environmental components and modulate ecosystem processes (e.g., productivity) (Feller et al. 2010).
Therefore, although mangrove forests are not very diverse in terms of plant species, they create habitats which support varied communities of other plants and animals (Feller et al. 2010, see Nagelkerken et al. 2008 for full review).

Mangrove taxonomy

There remains debate concerning the total number of true mangrove species; however the most recent global assessment considers 73 species and hybrids from 20 different families as true mangroves (Spalding et al. 2010). Hybrids are formed by cross-fertilization between two closely related species to produce offspring that share the characteristics of both parent species (Clough 2013). Out of 73 true mangrove species, 38 are also considered “core” mangrove plants because they dominate and characterize the flora in many locations (Spalding et al. 2010). Two families - *Avicenniaceae* and *Rhizophoraceae* - contribute the majority of core species. These two families dominate mangrove communities worldwide (MacIntosh and Ashton 2002).

The 62 mangrove species and hybrids of the Indo-West Pacific region. Species highlighted in bold are considered core mangrove species.

*Source: Spalding et al. 2010*

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**Rhizophora mangle**, which occurs throughout the AEP and **Rhizophora samoaensis**, which is found on a few islands in the Pacific, look very much the same. This has led some researchers to conclude that they may be a single species; however this has not been confirmed or widely agreed upon. The recent global mangrove assessment by Spalding et al. (2010), from which this table was adapted, treats these species as unique.

**This species is considered a hybrid by some researchers, while others regard it as a unique species**

### Differences in species distribution

Despite having similar total areas of mangrove habitat, the Indo-West Pacific (IWP) and Atlantic-East Pacific (AEP) regions have very different numbers of species and families (Spalding et al. 2010). The IWP has about twice the number of mangrove families and five times as many mangrove species as the AEP (Spalding et al. 2010). This regional pattern – floral diversity in the IWP exceeding that in the AEP - is also reflected at the local scale. Local mangrove tree diversity is typically 11-25 species in the IWP and 3-4 species in the AEP (Luther and Greenberg 2009). It is has been proposed that the IWP has such high species diversity compared to the AEP because it is where mangroves first evolved (Spalding et al. 2010).

### Mangroves and extinction risk

Unfortunately, the number of true mangrove species in many geographical areas is decreasing due to human activities (Hamilton and Snedaker 1984). All mangrove species are experiencing range declines from localized threats and habitat loss (Polidoro et al. 2010). However, some geographical areas are of special concern (Polidoro et al. 2010):

- **Indo-Malay Philippine Archipelago:** Globally, this is where mangrove biodiversity is the highest (Polidoro et al. 2010). While less than 15% of species which occur in this region are threatened, it also has some of the highest rates of mangrove loss (Polidoro et al. 2010). In Southeast Asia, large areas of mangroves have disappeared in the last 50 years, and much of the ones that remain are species poor (Ashton and MacIntosh 2002).

- **The Pacific and Atlantic coasts of Central America:** This region has the highest proportion of threatened mangrove species (Polidoro et al. 2010). The major reasons for extensive mangrove loss in Latin America are clearing for shrimp ponds, agriculture and human settlement (Lugo 2002).

A recent study by Polidoro et al. (2010) assessed extinction risk for mangrove species. This study revealed that approximately 16% of all mangrove species face an elevated threat of extinction (when only 70 true mangrove species were considered). Two species of special concern are listed as Critically Endangered (the highest probability of extinction) by the IUCN Red List: **Sonneratia griffithii** and **Bruguiera hainessi**. These species may be extinct within the next decade if not adequately protected.
The loss of individual mangrove species has direct economic consequences for human livelihoods, particularly in regions where species diversity is already low and there is low ecosystem resilience to species loss.

**Mangrove Associates**

Aside from true mangrove species, many other plant species which occur in coastal environments can also be found within, or on the periphery of the mangrove (Clough 2013). Mangrove associates are plants which are not limited to the mangrove; they also occur elsewhere (Baba et al. 2013). This group includes terrestrial plants as well as pure halophytes - plants which grow only in saline environments (Selvam 2007). Halophytic plants can be found within the mangrove, growing alongside true mangrove plants (Selvam et al. 2004). Other terrestrial species are less salt tolerant and therefore do not penetrate far into the mangrove or can be found growing in monospecific stands in elevated areas within the mangrove (Selvam et al. 2004).

There is no comprehensive inventory of mangrove associated flora; species will likely vary greatly between geographical regions and sites. However, in one example, approximately 268 plant species were recorded in a Southeast Asian mangrove and only 52 of these were considered ‘true mangroves’ (Giesen et al. 2007). The other plants included trees, vines, ferns, palms, grasses and herbs, as well as epiphytic varieties of orchids and mistletoes that grow on the trees (Giesen et al. 2007); demonstrating the diversity of mangrove associates which can exist. While mangrove associates contribute to the floral diversity of the ecosystem, they rarely form dominant plant communities (Clough 2013).

**2.2.2 Mangrove Fauna**

**Phytoplankton**

**Phytoplankton in the mangrove**

Plankton is a group of organisms which drift passively in the surface waters of aquatic environments (Kathiresan and Ajmal Khan 2011). Phytoplankton is unicellular microscopic algae. They are photosynthetic primary producers which form the base of the marine food webs. Phytoplankton communities in mangroves are diverse and are greatly influenced by local environmental conditions (Lee 1990). As such, they show distinct seasonal variations in abundance (Kathiresan and Bingham 2001). Populations respond to variations in temperature, salinity, the amount of tannins in the water (Kathiresan and Bingham 2001).

**Phytoplankton and productivity**

As photosynthetic organisms, phytoplankton contributes to primary production within the mangrove. It has been suggested that the contribution of phytoplankton to total net production in mangrove habitats ranges from 20-50% (Robertson and Blaber 1992), however, this number is variable. Production by plankton within the mangrove may be limited by high turbidity and lack of sunlight in shaded, narrow waterways (Kathiresan and Bingham 2001).
Phytoplankton and the mangrove food web

Although in some settings, phytoplankton may make only small contributions to total productivity, they can be critical to supporting higher trophic levels (Robertson and Blaber 1992) due to their greater nutritional quality relative to mangrove detritus (Kathiresan and Bingham 2001). Phytoplankton is preyed upon by zooplankton as well as sessile filter feeders such as sponges and ascidians (Feller and Sitnik 1996). Zooplankton, in turn, is consumed by higher predators such as juvenile fish (Robertson and Duke 1987, Chew et al. 2007).

Zooplankton

Introduction

Zooplankton is a diverse group of animals which are suspended and drift in bodies of water. Globally, they can be found in virtually every marine and freshwater environment. Mangroves support diverse communities of zooplankton, which attain high densities in these environments (Robertson and Blaber 1992). Zooplankton abundance within mangrove waterways can be much higher than in adjacent coastal waters (Robertson et al. 1988). Zooplankton is a major component of mangrove food webs. They feed on phytoplankton (single cell plants), and are in turn eaten by a wide variety of higher consumers, such as fish and birds. As such, zooplankton forms an important link in the food chain which connects primary production from plant organisms to larger carnivores.

The zooplankton community

The zooplankton community is not homogenous; it is represented by organisms belonging to many different taxonomic groups. While the majority of zooplankton are very small, too small to be seen with the naked eye (e.g., microzooplankton), some, such as jellyfish, can grow very large (e.g., macrozooplankton) (MacIntosh and Ashton 2002). In addition to being grouped according to their size, these organisms are grouped according to the proportion of their life cycle spent in the drifting, planktonic phase (Kathiresan and Ajmal Khan 2011). Some organisms spend their whole lives as plankton, while others are planktonic for only a specific developmental period:

- **Holoplankton:** Planktonic for their entire life cycle. Holoplankton occurs year-round.
  - e.g., foraminiferans, amphipods, krills, copepods, salps and some jellyfish
- **Meroplankton:** Planktonic for only part of their life cycle, usually the egg and larval stages. Meroplankton typically occurs in certain seasons.
  - After a period of time, meroplankton graduate to nekton (active swimmers) or adopt a benthic (bottom associated), sessile lifestyle. This group includes the larvae of crustaceans, marine worms and most fish. In some areas, meroplankton can account for more than 50% of plankton biomass (McConaugha 1992). Meroplankters, such as crustacean larvae is also an important dietary component of juvenile fish (Morgan 1990).

Importance in the mangrove

Zooplankton is an especially important food source for juvenile fish (Robertson and Blaber 1992), since zooplankton feeders are dominant among juvenile fish in mangroves (Robertson and Duke 1987, Chew
et al. 2007). Copepods frequently comprise the bulk of the zooplankton community in estuarine systems and are the main food for small or juvenile fishes (Bouillon et al. 2000, Robertson et al. 1988, Chew et al. 2007). Shrimp larvae are also an important source of juvenile fish nutrition (Chong and Sasekumar 1981). In this way, zooplankton communities play a critical role as intermediaries between carbon sources (detritus and phytoplankton) and secondary consumers (McKinnon and Klumpp 1997, Schwamborn 1997) which include some commercially important species.

**Bacteria and Fungi**
Actinomycetes are a group of bacteria well-known for their ability to produce chemical compounds which have pharmaceutical, industrial and agrochemical applications. Such chemicals include antitumor agents, antibiotics, enzymes and enzyme inhibitors (Sahoo and Dhal 2009). Mangroves are a rich source of antibiotic-producing actinomycetes (Sahoo and Dhal 2009). In many mangroves, research is being carried out to identify strains of actinomycetes of potential commercial value (e.g., Sweetline et al. 2012, Hunadanamra et al. 2013).

**Amphipods**
Amphipods are small to medium sized crustaceans (Kathiresan and Ajmal Khan 2011). Amphipods can be found in almost every ecosystem, including marine, freshwater and terrestrial habitats. Amphipods are good burrowers and construct tubes of mud or secreted material (Kathiresan and Ajmal Khan 2011). Some amphipods break down leaves into small particles, producing plant detritus, which is then consumed by other invertebrates (Camilleri 1992). Some amphipods also directly consume detritus. Amphipods thus play an important role in the conversion of plant and animal protein into food for larger animals (Kathiresan and Ajmal Khan 2011).

**Crabs**
**Introduction – crabs in the mangrove**
Crabs are characteristic mangrove crustaceans. Some species are directly dependent on the mangrove for survival, while others have ranges which overlap the mangrove and therefore are opportunistic visitors (Kathiresan and Bingham 2001). Mangrove crabs are well-adapted to their environment, often exhibiting distinct distributional patterns related to substrate characteristics, degree of tidal inundation, wave exposure and salinity (Kathiresan and Bingham 2001). Mangrove crabs can occur in very high densities. For example, the hermit crab, *Clibanarius laevimanus* rests on mangrove roots during low tide periods and has been observed in clusters of up to 5,000 individuals (Gherardi et al. 1991).

**Crabs in the mangrove**
Crabs belonging to the infraorder Brachyura (true crabs) are the most numerous fauna in mangrove ecosystems and certainly the most abundant crustaceans (MacIntosh and Ashton 2002). As a group, the Brachuryans in the mangrove are dominated by species from the families, Grapsidae (shore crabs) and Ocypodidae (ghost and fiddler crabs) (Jones 1984). Most mangrove grapsid crabs are from the subfamily Sesarminae (Lee 1998). Grapsid crabs in the Indo-Pacific play a significant role in the structure and
function of mangrove forests (Lee 1998). At low tide, crabs emerge from their burrows to feed on fallen mangrove leaves, propagules, fruits and algae that grow on mangrove roots. At high tide they retreat into their burrows to hide from predators and feed on leaves they have captured.

**Importance of mangrove crabs**

Due to their burrowing and leaf processing activity, grapsid crabs are viewed as “ecosystem engineers” (Kristensen 2008). Through these activities they modify the physical structure, substance chemistry and transport conditions of the sediment (Kristensen 2008). In doing so, they change the availability of resources for the associated microbial, fauna and plant communities (Kristensen 2008). By processing large amounts of leaf litter, they facilitate decomposition and help to retain forest production within the mangrove (Kristensen et al. 2010). In Neotropical mangroves, Ocypodidae crabs of the genus *Ucides* have now been shown to have the same role as Sesarmidae in terms of retention of forest products and organic matter processing (Cannicci et al. 2008).

**Importance of mangrove crabs**

Crabs are a very important source of food for other animals in the mangrove ecosystem. They are prey for fish, monkeys, birds, snakes, other crabs and humans. Some mangrove crabs are of substantial commercial value, for example, the mud crab, *Scylla serrata* (MacIntosh and Ashton 2002). Everywhere this crab occurs in the Indo-Pacific it is sought as a quality food item and is now farmed on a commercial scale in many tropical countries (Triño and Rodriguez 2002). Mud crabs use the mangrove fringe as nurseries and move out of the mangrove as they increase in size (Walton et al. 2006). Catch of mud crabs has been correlated with mangrove extent (Manson et al. 2005a). Habitat loss, along with overfishing, is contributing to reduced landings and smaller average capture size of mud crabs (Le Vay 2001).

**Prawns and Shrimp**

**Introduction**

Both prawns and shrimp are crustaceans belonging to the order, Decapoda because they have five pairs of legs. When broadly defined, the terms “prawn” and “shrimp” have been used interchangeably to describe any of the decapod crustaceans with elongated bodies that use swimming as a primary means of movement. Terminology also varies from country to country, but in general, the term "prawn" is loosely used to describe any large shrimp. The crustaceans of commercial value referred to as prawns mainly belong to one decapod family, Penaeidae. Those referred to as shrimps are usually members of the family, Caridea.

**Mangroves as nurseries**

Prawns and shrimp may complete their whole life cycle in offshore waters, or may spend all or part of their life cycle in mangroves. For many species, mangroves provide important nursery habitat
(Soundarapandian and Rajendran 2011, de Freitas 1986, Chong et al. 1990, Vance et al. 1990). This is true of the more commercial penaeid shrimps – those which are large in size and belonging to the genera *Penaeus*. These species use estuarine habitats as essential nursery grounds during early life stages (Dall et al. 1990). Adults of this group spawn at sea, and their larvae move inshore where the postlarvae settle in their preferred nursery grounds, either estuarine or other nearshore habitats (Dall et al. 1990). After a few months in the nursery, the juveniles migrate offshore to complete their life cycle.

**Mangroves - critical nurseries for some species**

Juvenile penaeid prawns occur in high densities in mangrove ecosystems (Daniel and Robertson 1990, Nagelkerken et al. 2008). A few species, the white banana prawn (*P. merguiensis*) (Staples et al. 1985), the red tail prawn (*P. penicillatus*) (Chong et al. 1990) and the Indian white prawn, (*P. indicus*) (Rönnbäck et al. 2002, Kenyon et al. 2004) are exclusively associated with mangroves (Nagelkerken et al. 2008). Several other species may occur in mangroves, but are also found in associated habitats such as mudflats and seagrass beds (Nagelkerken et al. 2008).

**Mangroves as nursery habitats**

As a nursery environment, the mangrove offers food and protection from predators. Mangroves produce large amounts of leaf litter that is converted to detritus. Dietary studies indicate that prawns do eat mangrove detritus (Chong and Sasekumar 1981; Robertson 1988); however juveniles seem to obtain most of their nutrition from animals that live on or within the muddy substrate. Prawns consume a wide variety of food items which occur in the mangrove forest, including crustaceans, bivalves, gastropods, zooplankton, polychaetes and insects (Chong and Sasekumar 1981, Moriarty and Barclay 1981, Robertson 1988, Wassenberg and Hill 1993). Tree roots, detritus and litter also create structural complexity which can reduce the visibility of vulnerable prawns (Meager et al. 2005). Additionally, the soft, muddy mangrove substrate is suitable for burrowing, which offers protection from predators (Meager et al. 2005).

**Importance of mangrove prawns and shrimps**

Prawns and shrimp are critical links in the mangrove food web. They are preyed upon by a wide variety of fish and other animals. Additionally, through their life cycle migrations, they transport nutrients between ecosystem boundaries; connecting the mangrove ecosystem to adjacent environments (Sheaves 2009). Many commercially important shrimp are associated with the mangrove. These include giant freshwater shrimp and large numbers of small shrimp which are dried and made into a paste that is a main ingredient in South East Asian cuisine (Rönnbäck 1999). Penaeid prawns are the most economically valuable fishery resource associated with mangroves (Rönnbäck 1999). The mangrove-dependent white banana prawn (*P. merguiensis*) is of particular commercial importance in the Indo-Pacific region (Loneragan et al. 2005). Catch of all prawns, as well as catch of just white banana prawns is often correlated with mangrove extent - where mangrove extent increases, so too does prawn catch (Pauly and Ingles 1986, Staples et al. 1985, Manson et al. 2005, Loneragan et al. 2005).
**Mangroves and prawn fisheries**

The exact nature of the relationship between mangrove presence and prawn catch in tropical nearshore waters is not entirely known. It may be that rather than mangrove abundance itself, the availability of organic matter and the extent of intertidal area may have a stronger influence on prawn catch (Lee 2004). It is likely that the relationship between commercial catch and mangroves will be specific to the species, location and time scale being considered (Nagelkerken et al. 2008). While the details concerning the relationship between mangroves and prawn catch are still being uncovered, mangroves seem to provide critical support to species which constitute valuable prawn fisheries.

**Mollusks**

**Introduction – mollusks in the mangrove**

Mangrove forests are characterized by a high abundance and diversity of mollusk species. The murky waters of the mangrove provide an abundance of food and the roots and soft sediments offer refuge from predators. This group is predominantly composed of gastropods and bivalves such as oysters, mussels, clams and snails (MacIntosh and Ashton 2002) and are some of the most visible animals in mangrove systems (Plaziat 1984). Most mollusks are relatively sessile filter feeders and thus are restricted to habitats below the average high water mark (Rönnbäck 1999). As a result, these species colonize mud banks, mangrove roots, and lower parts of tree trunks.

**Importance of mollusks in the mangrove**

Gastropods eat many types of food, including organic matter in the sediments, small plants, mangrove litter and propagules (Nagelkerken et al. 2008). The feeding activity of some mollusks, such as the mud whelk, *Terebralia palustris* helps decompose leaf litter and retain nutrients within the mangrove ecosystem (Fratini et al. 2004, Slim et al. 1997). In addition, they can modify the biological, chemical and physical properties of the soil surface through their movement (Carlen and Olafsson 2002). Mollusks themselves are preyed upon by a variety of consumers including birds, fish, monkeys and humans.

**Importance of mollusks in the mangrove**

Wood-boring bivalves are also common in the mangrove forest. Borers use wood as habitat and a food source (Brearley 2003). These mollusks can cause extensive damage to natural and man-made structures. Although they may be a nuisance to humans, they perform an important function in the mangrove community. Borers facilitate the breakdown of wood and increase the surface area of dead wood that can be colonized by other organisms such as bacteria (Brearley 2003). Additionally, their excrement is a nutrient source for other boring organisms and the animals themselves are food other predatory mollusks (Barkati and Tirmizi 1991, Rimmer et al. 1983).

**Mangroves and mollusk fisheries**

Mangroves support productive mollusk fisheries of considerable subsistence and commercial value in many regions of the world. Mangrove oysters, mussels and marine clams (sometimes called cockles) are
collected as a local food source in several coastal regions. For example, *Cerithidea obtusa* is a common snail eaten in Thailand (McCoy and Chongpeepien 1988). Similarly, the oyster, *Crassostrea tulipa* is harvested in The Gambia and constitutes an important source of local income (Van Lavieren 2012). Cockles are also an important source of nutrition and economic income in The Gambia, Tanzania and Nicaragua (Van Lavieren et al. 2012, Crawford et al. 2010).

**Mangroves and mollusk fisheries**

In the past, natural stocks of mollusks were large enough to meet human demand (Hamilton and Snedaker 1984) and people collected mollusks by gleaning- harvesting with simple tools or by hand in the intertidal zone (Crawford et al. 2010). This situation has been altered dramatically through the overharvesting of mollusk populations and degradation and destruction of productive mangrove habitat. While gleaning still occurs, in some areas yield is supplemented by the provision of artificial substrates for settlement and growth of mollusks. This not only encourages additional settlement and growth of mollusks, but also reduces the likelihood of damage during harvesting.

**Reptiles**

Many types of reptiles commonly occur in mangrove forests, including lizards, crocodiles, and snakes. Some reptiles are top predators in the mangrove.

- **Crocodiles**
  The most recognized reptiles found in mangroves are crocodiles. This group includes the world’s largest living reptile, the estuarine crocodile (*Crocodylus porosus*) which is distributed from East India and Sri Lanka throughout Southern China to Thailand, the Philippines, North Australia and some Pacific Islands (Campbell et al. 2010). This crocodile species can grow to 7-8 m in length and eats fish, crustaceans and large mammals. Other crocodiles which inhabit mangroves include caimans, found in Central and South America and the African Nile crocodile (*Crocodylus niloticus*) (MacIntosh and Ashton 2002). Although crocodiles can use non-mangrove habitats, as nurseries for fish and other prey items of the crocodile, mangroves serve as an important feeding ground. Additionally, vulnerable crocodile hatchlings may seek refuge among mangrove roots (Santiapillai and de Silva 2001). In some mangroves, crocodile populations have drastically declined due to habitat loss and human encroachment (Kathiresan and Bingham 2001).

- **Snakes**
  Both terrestrial and marine snakes are known to permanently reside or frequently visit mangroves. Some snakes are specialists to mangroves, such as the gold-ringed cat snake (*Boiga dendrophila*) and the mangrove pit viper (*Trimeresurus purpureomaculatus*) which occur throughout Southeast Asia and India and the mangrove water snake (*Nerodia clarkii compressicauda*) of Florida. Other snakes enter the mangrove opportunistically to forage for prey items including king cobras (*Ophiophagus Hannah*) and pythons (MacIntosh and Ashton 2002). Although the banded sea snake *Laticauda colubrina* is primarily associated with reef habitats, they also may shelter in adjacent habitats such as mangroves (Heatwole et al. 2005).
• **Turtles and Lizards**

Other mangrove reptiles include turtles and lizards. Several lizard species, ranging from geckos to iguanas, inhabit mangrove forests. The mangrove monitor lizard (*Varanus indicus*) can reach up to 1m in length and is an opportunistic carnivore, feeding on the eggs of reptiles and birds, mollusks and rodents. Marine and freshwater turtles are also found periodically in mangroves. The mangrove terrapin (*Batagur baska*) (from Central and Southeast Asia), and the critically endangered painted terrapin (*Batagur borneoensis*) of the Sundarbans are two freshwater species which inhabit tidal creeks and rivers (Nagelkerken et al. 2008, IUCN 2006).

**Mammals**

**Introduction**

Few mammals permanently inhabit the mangrove forest, most reside in adjacent habitats, but visit the mangrove for various reasons. However, mangroves in some regions are home to very rare and charismatic mammals which are highly dependent on these habitats. For these mammals, protecting the mangrove environment is critical to the survival of the species.

• **Monkeys**

Monkeys are common visitors to mangroves and some are exclusively associated with these habitats. Long-tailed macaques (*Macaca fascicularis*) in Southeast Asia forage in mangroves for crabs, oysters, snails and small invertebrates (MacIntosh and Ashton 2002). They have even been observed using discarded oyster shells to crack open other oysters attached to the roots and lower branches of mangrove trees (Malaivijitnond et al. 2007). The endangered proboscis monkey (*Nasalis larvatus*) is endemic to Borneo where it is restricted to riverine, peat swamp and mangrove forests of the coastal lowlands. This species relies heavily on mangrove trees for food and shelter (MacIntosh and Ashton 2002). Although it is a tourist attraction for the area, this species is in decline due mainly to habitat destruction; clearing of riverbanks and mangroves in particular has had a significant impact on populations (Meijaard et al. 2008)

• **Bats**

Fruit and insect eating bats are attracted to mangroves for the abundance of food they provide. In some cases they can fill an important ecological role, acting as plant pollinators. For example, the cave fruit bat (*Eonycteris spelea*) and the long-tongued fruit bat (*Macroglossus minimus*) feed on the pollen and nectar of *Sonneratia* plants and are major pollinators of *Sonneratia* (MacIntosh and Ashton 2002). Throughout northern Australia, large bats, often referred to as flying foxes can be found roosting in mangrove trees.

• **Aquatic Mammals**

Aquatic mammals are observed among the mangroves periodically. Dugongs, manatee, hippopotamuses and some dolphins and porpoises are a few examples of those which can be seen in mangroves. Although none of these directly feed on mangroves, they may benefit from shelter provided by the mangrove channels (Spalding et al. 2010). In the Sundarbans, the Irrawaddy and Gangetic dolphins (*Orcaella brevirostris* and *Platynista gangetica* respectively) are some charismatic, but threatened species (Gopal and Chauhan 2006). Smooth- and small-clawed otters (*Lutra perspicillata* and *Aonyx cinerea*) are
also found in some Asian mangroves. Preservation of mangrove habitat is critical to the survival of these species (Foster Turley 1992).

- **Other Mammals**

  Other mammalian visitors to mangroves include deer, wild pigs and rodents. Examples from these groups are found all around the world. One of the largest rodent species, the Cuban hutia can be found in Cuban mangroves. This endemic rodent species can weigh up to 8.5kg. In India, large populations of the spotted deer (*Axis axis*) and wild boar (*Sus scrofa*) inhabit the Sundarbans mangroves in Bangladesh (Gopal and Chauhan 2006). Both of these species are favored prey items of the Bengal tiger (*Panthera tigris tigris*) (Gopal and Chauhan 2006).
2.3 Methods for Assessing Biodiversity

Why Study Biodiversity?
There are mainly three reasons why biodiversity should be studied. First, the need has come as mangrove forests have been ruthlessly exploited and cleared for various reasons. Coral reefs have been indiscriminately mined. The fishery resources have been overexploited. Many other organisms have been exterminated for ornamental and medicinal purposes. There has been widespread degradation of the habitats. Due to industrial development and large scale use of pesticides and insecticides in agriculture, the pollution load has increased in the estuaries, mangroves backwaters and seas. Measures of diversity are frequently seen as indicators of the wellbeing of ecological systems. Secondly, despite changing fashions and preoccupations, diversity has remained the central theme of ecology. Thirdly, considerable debate surrounds the measurement of diversity. It is mainly due to the fact that ecologists have devised a huge range of indices and models for measuring diversity. So for the various environments, habitats and situations the species abundance models and diversity indices should be used and the suitability evaluated.

Assumptions of biodiversity assessment
The assessment is based on three assumptions. The first assumption is that all species are equal. No special weightage is given to any particular species. The species that are exceptionally abundant and those which extremely rare are treated equally. The second assumption is that all individuals are equal. As far as biodiversity assessment is concerned, there is no difference between the largest and the minute organisms. Finally all the biodiversity assessment method assume that species abundances have been recorded using appropriate and comparable units. Abundance must be in the form of number of individuals. It is unwise to include different types of abundance measure such as number of individuals and biomass in the same investigation. Diversity estimate based on different units are not directly comparable.

How to choose a diversity index?
It is very tempting to calculate a range of diversity measures, especially if one is using a statistical package that will do this automatically. This temptation must be resisted. It is important to know in advance which aspect of biodiversity is being investigated and why, since this will have implications for the sampling design etc., and not simply to choose the measure that provides the most attractive answer. As biodiversity is considered as a synonym of species richness, selection of an appropriate richness measure will be ideal (Simpson, Margalef and Menhinick). If a heterogeneity measure is selected, the Simpson diversity index provides a good estimate of diversity at relatively small sample sizes. Despite its popularity, use of Shannon index needs much stronger justification. Given its sensitivity to sample size, there appears to be few reasons for choosing it over other indices. However the Shannon index seems likely to persist since many long-term investigations have chosen it as their benchmark measure of biological diversity. The Berger-parker index provides is a simple and easily interpretable dominance. Likewise, there are advantages in using the Simpson evenness measure particularly if the
Simpson index has been used to describe diversity. Taxonomic distinctness measures are informative and easily interpretable and have the added advantage of being robust against variation in sampling effort.

**Adequacy of sampling**
The sample size must be adequate to meet the objective of the investigation. Replication is strongly recommended. All other things being equal it is almost always better to have many small samples rather than a single large one. Replication means that statistical analysis is possible and allows confidence limits to be constructed. Repeated sampling is also the key to species richness estimation and means that jackknifing and bootstrapping are feasible.

**Biodiversity Indices**
Given the large number of indices, it is often difficult to decide which the best method of measuring diversity is. One good way to get a feel for diversity measures is to test their performance with one’s own data. A more scientific method of selecting a diversity index is on the basis of whether it fulfils certain functions criteria—ability to discriminate between sites, dependence on sample size, what component of diversity is being measured, and whether the index is widely used and understood. The various diversity measures found in literature are given below.

**Species Richness Indices**

**Simpson’s Index**
Simpson gave the probability of any two individuals drawn at random from an infinitely large community belonging to different species. The Simpson index is therefore expressed as $1 - D$ or $1/D$. The merit of this index is that it is a widely used measure of richness. The demerit of this index is that it is heavily weighed towards the most abundant species. It has been shown that once the number of species exceeds 10 the underlying species abundance distribution is important in determining whether the index has a high or low value.

**Margalef Index**
It is having a very good discriminating ability. It is very easy to calculate. The formula used is $D_Mg = \frac{(S - 1)}{\ln N}$. It is a measure of the number of species present for a given number of individuals. The demerit of this index is that it is sensitive to sample size. This index fails to discriminate situations where $S$ and $N$ are identical but evenness varies. The advantage of this index is that values can come more than 1 unlike Simpson index where the values are in the range of 0 - 1. This way comparing the species richness between different samples collected from various habitats is easy using this index.

**Menhinick index**
This index has also a very good discriminating ability. The formula used for calculating this index is $D_{Mn} = \frac{S}{\sqrt{N}}$. It is also a measure of number of species present for a given no. of individuals. The merit of this
index is that it is very easy to calculate. The demerits are that it is influenced by the sample size and it fails to discriminate situations where S and N are identical but evenness varies.

**Rarefaction Index**
Even though it is used for standardizing the sample size, it is also used an index (Hsieh and Li 1998). This index relates sample size (number of organisms) with numbers of species. This is very much helpful in comparing the diversity of organisms living in healthy and degraded environments.

**Species Diversity Indices**
These indices are synonymous with ecological quality. Two types of diversity measures are there namely Parametric and Nonparametric. The parametric methods include Log series $\alpha$, Log normal $\lambda$ and $Q$ statistic. The nonparametric methods include Shannon-Wiener index, Expected $H'$, Maximum Shannon diversity, The Brillioun index and McIntosh’s measure of diversity.

**Parametric methods**
**Log series ($\alpha$) index**
It is used to calculate diversity for a normally distributed population. It is reported to be a satisfactory measure of diversity, even when the underlying species abundances do not follow a log series distribution. This popular method is very widely used because of its good discriminating ability and the fact that, it is not unduly influenced by sample size. This index is less affected by the abundances of the commonest species. This is a popular and very widely used index. This is not influenced by the sample size. It has good discriminating ability. It can be read from a nomograph when $S$ (number of species) $N$ (total number of individuals) are known.

**Log normal ($\lambda$) index**
Used when log normal distribution is there. It is independent of the sample size. That way it is very efficient for comparing diversity between habitats. However it cannot be accurately estimated when the sample size is small. Therefore the sample size has to be large. It can also be used as a measure of evenness. Under stress, log normal distribution changes to geometric series.

**$Q$ statistic**
It is an innovative approach to diversity measurement. It takes in to consideration the distribution of species only and does not entail fitting a model like the above two indices. It measures inter-quartile slope of the cumulative species abundance curve and provides an indication of the diversity of the community.

**Nonparametric methods**
**Shannon-Wiener Index**
It is a benchmark measure of biological diversity and denoted as $H'$. 
It is a widely used measure of diversity index for comparing diversity between various habitats (Clarke and Warwick 2001). Shannon and Wiener independently derived the function which has become known as Shannon index of diversity. It is often wrongly called as Shannon and Weaver index because the original formula was published in a book by Shannon and Weaver (1949). It is derived from information theory – on the rationale that diversity or information in a natural system can be measured in a similar way to the information contained in a code or a message. This indeed assumes that individuals are randomly sampled from an infinitely large population. The index also assumes that all the species are represented in the sample. \( \log_2 \), \( \log_{10} \) and the natural logarithm can be used for calculating this index. However \( \log_2 \) is often used for historical reasons to compare data collected presently with earlier. It is of course essential to be consistent in the choice of log base when comparing diversity between samples. The value of Shannon diversity is usually found to fall between 1.5 and 3.5 and only rarely it surpasses 4.5. It has been reported that under log normal distribution, \( 10^5 \) species will be needed to produce a value of Shannon diversity more than 5. It is used extensively in pollution research.

**Demerits of Shannon-Wiener Index**

It is a dubious method with no direct biological interpretation. However it is a notoriously popular method. Influenced very much by sample size. Therefore it is weighted slightly towards species richness. Interpretation is at times difficult. Difficult to differentiate \( H' = 2.35 \) from \( H' = 2.47 \). For the above, values of \( eH' \) values are 10.49 and 11.82 respectively. Therefore \( eH' \) is better than \( H' \)

**Expected \( H' \) (\( eH' \))**

It can be used as an alternative to \( H' \). It is equivalent to the number of equally common species required to produce the value of \( H' \) of the sample.

**Maximum Shannon diversity**

It is denoted as \( H_{max} \). The observed diversity (\( H' \)) is always compared with maximum Shannon diversity (\( H_{max} \)) which could possibly occur in a situation where all species are equally abundant.

**Brillouin Index**

The Brillouin index is used instead of the Shannon index when diversity of non-random samples or collections is being estimated. For instance, fishes collected using the light produce biased samples since not all the fishes are attracted by the light. The Brillouin index is used here to calculate the diversity of fishes collected by gears which use light for fishing. It is denoted as \( BH \). This index always produces lower value than Shannon as it describes a known collection about which no uncertainty is there. Shannon by contrast calculates the diversity of sampled / unsampled portion of community.
McIntosh’s Measure of Diversity
Mcintosh proposed that a community could be envisaged as a point in an S dimensional hyper volume and that the Euclidian distance of the assemblage from the origin could be used as a measure of diversity. This index is denoted as U. The demerit of this index is that it is influences by evenness.

Species Evenness Indices
Evenness index is also an important component of the diversity indices. This expresses how evenly the individuals are distributed among the different species. Pielou’s evenness index is commonly used. Heip evenness index is also there but comparatively less used.

Dominance indices
Simpson’s dominance index
This index is denoted as D. Used in pollution monitoring studies-Environmental Impact Assessment (EIA). When D increases, diversity decreases. When diversity increases, dominance decreases.

Berger-Parker Index
This index is also denoted as D. It is a simple easily interpretable measure of dominance. This simple intrinsic index expresses the proportional importance of the most abundant species. It is easy to calculate. As with the Simpson index, the reciprocal form of the Berger-Parker index is usually adopted so that an increase in the value of the index accompanies an increase in diversity and a reduction in dominance.

Other indices
Hill Numbers
Hill (1973b) proposed a unification of several diversity measures in a single statistic. While \( N_0 \) is equivalent to species richness, \( N_1 \) is equivalent of Shannon diversity, \( N_2 \) the reciprocal of Simpson’s and \( N_{\text{inf}} \) is the Berger Parker index. The advantage is that instead of calculating various indices for diversity, richness and evenness, it can be used to calculate all these measures. That is its advantage.

Caswell Neutral Model /’V’ Statistics
This is helpful in comparing the observed diversity with the diversity provided by the neutral model (Caswell 1976). This model constructs an ecologically neutral community with the same number of species and individuals as the observed community assuming certain community assembly rules (random birth/deaths and random immigration/emigrations and no interaction between species). The deviation statistics ‘V’ is then determined which compares the observed diversity (\( H' \)) with that predicted from the neutral model \( [E(H)] \). While the ‘V’ value of zero indicates neutrality, positive values indicate greater diversity than predicted and negative values lower diversity. Values > +2 or <-2 indicate significant departure from neutrality.
Newly Introduced Indices
Taking into consideration the demerits of the routinely used conventional indices, new indices have been recently introduced. Conventional indices are heavily dependent on sample size/effort. In view of this, indices with similar effort only can be compared. But with respect to the conventional indices, the effort is not mentioned. Also, the old indices do not reflect the phylogenetic diversity. There is also no statistical framework for testing the departure from expectation and the response of species richness to environmental degradation is not monotonic. Lastly, there is no way of distinguishing natural variation from anthropogenic disturbance. The newly introduced diversity measures (Warwick and Clarke 1995) do not have these demerits.

Taxonomic Diversity Index
It is defined as the average taxonomic distance between any two individuals (conditional that they must belong to two different species) chosen at random along the taxonomic tree drawn following the Linnaean classification. When the sample has many species, the values are on the higher side reflecting the taxonomic breadth.

Taxonomic Distinctness Index
It is defined as the average path length between any two individuals (conditional that these must belong to two different species) chosen at random along the taxonomic tree drawn using the Linnaean classification. Here also, the higher values reflect the higher diversity of samples. Another advantage of this index is that making use of the average taxonomic distinctness and variation in taxonomic distinctness index, biodiversity between healthy, moderately degraded and heavily degraded habitats could be compared using the 95% histogram, 95% funnel, and ellipse plots. Another feature of this index is that in the absence of quantitative data, the above could be accomplished based on qualitative data.

Phylogenetic Diversity Index
The total phylogenetic diversity index denotes the taxonomic breadth/total taxonomic path length and the average phylogenetic index is obtained by dividing the total phylogenetic diversity index by the number of species. In a healthy environment due to rich faunal assemblages, (taxonomic breadth) the total phylogenetic diversity and average phylogenetic diversity are always more. The following hypothetical data of mangroves explain the efficiency of the newly used diversity indices which capture the higher level diversity also efficiently (genera and families). In island 1 there are 12 species of mangroves, belonging to 12 genera and 12 families. But in island 2, the same number of species are there but belonging only to 5 genera and 4 families.

Species estimators
There are three approaches for estimating species richness from samples. The first of these depends on the extrapolation of species accumulation or species-area curves. Alternatively, it is possible to use the shape of the species abundance distribution to deduce total species richness. The final and potentially most powerful approach is to use a nonparametric estimator.
Nonparametric estimators

The following species estimators can be used to find out the likelihood of obtaining the maximum number of species one is likely to encounter with more effort.

1. Chao 1
2. Chao 2
3. Jacknife 1
4. Jacknife 2
5. Bootstrap
6. Michaelis Menton
7. ACE (abundance-based coverage estimate)
8. ICE (incidence-based coverage estimate)

Chao 1

It is a simple estimator of the absolute number of species in an assemblage. It requires abundance data for calculating the maximum possible number of species with intensification of effort. It is based on the number of rare species in sample. The equation used is \( S_{Chao1} = S_{obs} + \frac{F_1^2}{2F_2} \), where, \( S_{obs} \) = No. of species in the sample, \( F_1 \) = No. of species represented by a single individual in a single sample (singletons) and \( F_2 \) = No. of species represented by two individuals (doubletons). It is a function of the ratio of singletons and doubletons. It increases as the relative frequency of singletons increases.

Chao 2

The above (Chao 1) is modified for use with presence / absence data. The equation used is \( S_{Chao2} = S_{obs} + \frac{Q_1^2}{2Q_2} \), where, \( Q_1 \) = Number of species in one sample only and \( Q_2 \) = Number of species in two samples only. The merit of this estimator is that it performs well and accurately predicts richness.

Jacknife 1

It was originally used in mark-recapture experiment. Subsequently it is being used for species richness estimation. The equation used is \( S_{Jack1} = S_{obs} + Q_1(m-1/m) \) where, \( Q_1 \) = number of species in one sample only and \( m \) = number of samples. For calculation, this estimator requires incidence data.

Jacknife 2

Like Chao 2 it takes both number of species found in one sample only and in precisely two samples. It also requires incidence data. The equation used is:

\[
S_{Jack2} = S_{obs} + \left[ \frac{Q_1(2m-3)}{m} - \frac{Q_2(m-2)^2}{m(m-1)} \right]
\]

where \( Q_1 \) = number of species in one sample only and \( Q_2 \) = number of species in two sample only. The merit of this estimator is that it performs well and accurately predicts richness.
**Bootstrap**
It also requires only incidence data. The equation used is \( S_{\text{boot}} = S_{\text{obs}} + \sum (1- p_k)^n \) where, \( p_k \) is proportion of samples that contain species \( k \). It gives good results when rare species are present.

**Michaelis Menton**
It estimates species richness using a model.

**ACE (abundance-based coverage estimate)**
This is based on the abundance of the species between one and ten individuals. It is calculated using the following equation:

\[
S_{\text{ACE}} = S_{\text{abund}} + \frac{S_{\text{rare}}}{C_{\text{ACE}}} + \frac{F_1}{C_{\text{ACE}}} \gamma^2 \text{ACE}
\]

where \( S_{\text{rare}} \) = number of rare species (less than ten individuals), \( S_{\text{abund}} \) = number of abundant species (more than ten individuals), \( F_1 \) = number of singletons, \( C_{\text{ACE}} = 1-F_1 / N_{\text{rare}} \) and \( \gamma^2 \text{ACE} = \text{C.V of } F_1 \).

**ICE (incidence-based coverage estimate)**
This is also based on the incidence data. It is calculated using the following equation:

\[
S_{\text{ICE}} = S_{\text{freq}} + \frac{S_{\text{infr}}}{C_{\text{ICE}}} + \frac{Q_1}{C_{\text{ICE}}} \gamma^2 \text{ICE}
\]

where \( S_{\text{infr}} \) = number of infrequent species found in less than ten samples, \( S_{\text{freq}} \) = number of common species found in more than ten samples, \( Q_1 \) = number of uniques, \( C_{\text{ICE}} = 1-Q1 / N_{\text{infr}} \) and \( \gamma^2 \text{ICE} = \text{C.V of } Q_1 \).

**Abundance/Biomass Comparison (ABC) Plots**
The advantage of distribution plots such as k-dominance curves is that the distribution of species abundances among individuals and the distribution of species biomasses among individuals can be compared on the same terms. Since the two have different units of measurement, this is not possible with diversity indices. This is the basis of the Abundance/Biomass Comparision (ABC) method of determining levels of disturbance (pollution-induced or otherwise) on benthic communities. Under stable conditions of infrequent disturbance the competitive dominants in benthic communities are k-selected or conservative species, with the attributes of large body size and long life-span: these are rarely dominant numerically but are dominant in terms of biomass. Also present in these communities are smaller r-selected or opportunistic species with a short life-span, which are usually numerically dominant but do not represent a large proportion of the community biomass. When pollution perturbs a
community, conservative species are less favoured and opportunistic species often become the biomass dominants as well as the numerical dominants. Thus under pollution stress, the distribution of numbers of individuals among species behaves differently from the distribution of biomass among species. The ABC method, involves the plotting of separate k-dominance curves for species abundances and species biomasses on the same graph and making a comparison of the forms of these curves. The species are ranked in order of importance in terms of abundance or biomass on the x-axis (logarithmic scale) with percentage dominance on the y-axis (cumulative scale). In undisturbed communities the biomass is dominated by one or few large species, each represented by rather few individuals, whilst the numerical dominants are small species with a strong stochastic element in the determination of their abundance. The distribution of number of individuals among species is more even than the distribution of biomass, the latter showing strong dominance. Thus, the k-dominance curve of biomass lies above the curve of abundance for its entire length. Under moderate pollution, the large competitive dominants are eliminated and the inequality in size between the numerical and biomass dominants is reduced so that the biomass and abundance curves are closely coincident and may cross each other one or more times. As pollution becomes more severe, benthic communities become increasingly dominated by one or a few very small species and the abundance curve lies above biomass curve throughout its length. These three conditions (unpolluted, moderately polluted and grossly polluted) can be easily recognized in a community without reference to the control samples. That is the advantage of this ABC plot (Clark and Warwick 2001)

**Dominance Plot**

Dominance plot is also called as the ranked species abundance plot. This can be computed for abundance, biomass, %cover or other biotic measure representing quantity of each taxon (Clarke and Warwick 2001). For each sample, or pooled set of samples, species are ranked in decreasing order of abundance. Relative abundance is then defined as their abundance expressed as a percentage of the total abundance in the sample, and this is plotted across the species, against the increasing rank as the x axis, the latter on a log scale. On the y axis either the relative abundance itself or the cumulative relative abundance is plotted, the former therefore always decreasing and the latter always increasing. The cumulative plot is often referred to as a k-dominance plot. The cumulative curve is used for comparing the biodiversity. When k-dominance curve is used for comparing the biodiversity between many habitats, it is called as multiple k-dominance curves. Here the sample representing the lower line has the higher diversity. In the relative dominance curve, the curves representing samples from polluted sites will be J-shaped, showing high dominance of abundant species, whereas the curves for less polluted habitats will be flatter. In the cumulative dominance plot, the curves for the unpolluted sites will be sigma shaped and the curves for the polluted habitats will be elevated (rises very quickly).

**Geometric Class Plots**

These are essentially frequency polygons, plotted for each sample, of the number of species that fall in to a set of geometric (x2) abundance classes. That is, it plots the number of species represented in the sample by a single individual (class 1), 2 or 3 individuals (class 2), 4-7 individuals (class 3), 8-15
individuals (class 4) etc. It has been suggested that impact on assemblages tends to change the form of this distribution, lengthening the right tail (some species become very abundant and many rare species disappear) and giving a jagged curve.

**Species Area Plot**
It is a curvilinear curve, plotting the cumulative number of different species observed as each new sample is added (Clarke and Warwick 2001). The curve which rises further and further with addition of sample is more diverse than the one which has attained the plateau. It is also used for deciding the number of samples to be collected in a particular habitat to get all the species.

**Conclusion**
The variety of diversity measures, species abundance models and graphical tools available help ably in assessing the biodiversity of all the habitats. The advancement in computer technology has made biodiversity studies more easy and interesting. However this development should be made good use of in protecting the very rich biodiversity our country is blessed with.
3.0 Mangrove Management and Restoration Tools

3.1 Ecosystem-based Management

Ecosystem-based management, or EBM, is an approach that goes beyond examining single issues, species, or ecosystem functions in isolation. Instead it recognizes ecological systems for what they are: a rich mix of elements that interact with each other in important ways. This is particularly important for oceans and coasts. For example a single commercially valuable fish species, for example, may depend on a range of widely separated habitats over its lifetime, depending on whether it is young or adult, feeding, spawning, or migrating. It needs access to each habitat at the right time, as well as ample food, clean water, and shelter.

Ecosystems are found on land, in sea, and air, and include a variety of interconnected habitats and species. Humans are fully part of ecosystems, too. As such, urban and transformed landscapes must also be considered in ecosystem-based management.

EBM is aimed at conserving and sustaining ecosystem services to benefit current and future human generations.

Other related terms:
Integrated coastal zone management or Integrated coastal management is a process for the management of the coast using an integrated approach, regarding all aspects of the coastal zone, including geographical and political boundaries, in an attempt to achieve sustainability.
Integrated watershed and coastal area management

Ridge to reef: The world’s oceans, rivers, lakes, and groundwater systems do not respect political borders. These large water systems cover most of our planet, and must be protected as an integrated system.

Why Ecosystem-based Management of Oceans and Coasts?
Healthy marine and coastal ecosystems provide many valuable services – from food security, resources for economic growth and recreation alongside tourism and coastline protection. They are also recognized as crucial reservoirs of biodiversity at a time when the loss of species on both land and in the sea is an increasing cause for concern. A major reason for management failure is conflict: between various uses, between the cultures of different user groups, and between jurisdictions charged with management. Vested interests are clashing. There is also fragmentation of jurisdictions and decision-making. Coastal planners look almost exclusively at the terrestrial side of the coastal zone. Watershed management authorities focus on freshwater flows. Fisheries managers address exploitation of fish
(often a single stock at a time). Shipping authorities take responsibility for ports, ship traffic, and safety at sea. Navies address national security interests. Conservationists and environmental ministries protect threatened species, reefs, and wetlands. Developers and tourism ministries eagerly eye sites for new resorts. And local communities interject their own needs and demands for economic, social, and environmental management in the mix, not always with an ecologically sound vision. This approach fails to consider how these multiple and cumulative uses can affect ecosystems.

EBM recognizes that our welfare and the health of the environment are linked. Put another way, marine and coastal systems provide valuable natural services, or “ecosystem services”, for human communities. Therefore, to protect our long-term wellbeing, we need to make sure marine and coastal ecosystem functions and productivity are managed sustainably. This means managing them in a way that acknowledges the complexity of marine and coastal ecosystems, the connections among them, their links with land and freshwater, and how people interact with them.

EBM involves two changes in how management is practiced:

(1) each human activity is managed in the context of ALL the ways it interacts with marine and coastal ecosystems, and

(2) multiple activities are being managed for a common outcome.
Core Elements
To describe this, the terms **ecosystem-based management** and **ecosystem approach** (EA) are often used interchangeably, and they mean generally the same thing. Although the term “ecosystem-based management” has been defined in numerous ways, the core elements of it include:

- **Recognizing connections** among marine, coastal, and terrestrial systems, as well as between ecosystems and human societies.
- **Using an ecosystem services perspective** where ecosystems are valued not only for the basic goods they generate (such as food or raw materials) but also for the important services they provide (such as clean water and protection from extreme weather).
- **Addressing the cumulative impacts** of various activities affecting an ecosystem.
- **Managing for multiple objectives** and balancing multiple and sometimes conflicting objectives that are related to different benefits and ecosystem services.
- **Embracing change, learning from experience, and adapting** policies throughout the management process.

Human activities on land and in the ocean are changing coastal and marine ecosystems and threatening their ability to provide important benefits to society, such as healthy and abundant seafood, clean beaches, and protection from storms and flooding. EBM is an innovative management approach to address these challenges. It considers the whole ecosystem, including humans and the environment, rather than managing one issue or resource in isolation. Key aspects of EBM include:

- Integration of ecological, social, and economic goals and recognition of humans as key components of the ecosystem.
- Consideration of ecological- not just political- boundaries.
- Accounting for the complexity of natural processes and social systems and using an adaptive management approach in the face of resulting uncertainties.
- Engaging multiple stakeholders in a collaborative process to define problems and find solutions.
- Incorporating understanding of ecosystem processes and how ecosystems respond to environmental perturbations.
- Concerned with the ecological integrity of coastal-marine systems and the sustainability of both human and ecological systems.

Taken together, these core concepts set ecosystem-based management apart from traditional management. They are key overarching considerations as the practitioner begins to implement EBM. It is important to note, however, that although all of these elements are essential, they can be addressed incrementally given the situation and existing programs in a particular area.
Recognizing connections
In designing management schemes for mangroves, it is crucially important that connections are recognized among marine, coastal, and terrestrial systems, as well as between ecosystems and human societies.

Recognize connection between ecosystems and human activities

(Source: UNEP 2011)

Recognize connections between ecosystems

Connecting ecosystems

(Source: UNEP 2011)
Incorporate species connections to different ecosystems

Recognize all connections in designing Protected Areas
An ecosystem based and integrated approach with protected areas needs to be applied through the establishment of networks or systems of protected areas within or between countries is now widely recognized as a means of building resilience and encouraging more rapid recovery in response to extreme impacts. See the Section on Protected Areas in this manual for more on this topic.

Recognize Cumulative Impacts
The human activities that take place within an ecosystem often overlap with each other, and their impacts can be intensified as a result. Impacts can also accrue over time. By examining such cumulative impacts, it is possible to assess the total effect of various human actions on an ecosystem, as well as that ecosystem’s ability to sustain delivery of desired services
Manage for multiple objectives

EBM focuses on the diverse benefits provided by marine and coastal systems rather than on single ecosystem services. Such benefits or services include vibrant commercial and recreational fisheries, renewable energy from wind or waves, coastal protection, and recreation. Fundamentally, the primary goal of any EBM project is to secure the long-term delivery of multiple ecosystem services that support human wellbeing by sustaining critical ecosystem structures, functions, and processes.
3.2 Protected Areas

Mangroves and Protected Areas
The most widely utilized form of protection has come from the designation of mangroves within protected areas, established for conservation purposes. Protected areas can help prevent mangrove loss and degradation in specific locations. Protected areas can provide social, economic and environmental benefits, both directly through more sustainable management of resources, or indirectly thorough protection of ecosystem services. Protected areas, which by definition are established for conservation benefits, fall under various levels of protection, from forest management for sustainable harvest to strict nature reserves. Unfortunately, many of these protected areas are poorly designed or poorly enforced and some fail to prevent mangrove loss and degradation within their boundaries.

It is estimated that there are some 1200 protected areas worldwide that include mangroves, covering approximately 25 per cent of all remaining mangrove areas. This level of protected areas coverage is considerably higher than the global terrestrial average of 13 per cent, or the average for forests (Chape et al. 2008). There are still large gaps in protected area coverage – notably in much of the Red Sea, Myanmar, the Solomon Islands, Fiji, and West and Central Africa.

Although many protected areas are so-called ‘paper parks’ that exist legally, but where regulations are poorly enforced or are insufficient to create any real level of protection, even these very poorly protected sites are valuable –because their limited protection is better than none at all. Protected areas are a powerful tool for ensuring the protection of mangrove biodiversity and should form part of a wider management regime. Successful protected areas require community engagement and clear legal and management structures. Protected areas are extremely attractive for tourists to visit, but it is important to know that the purpose of a protected area is to maintain habitat for flora and fauna, allowing species to exist and thrive without human interference. Whenever visiting a protected area, the visit should be made with minimal impact.
Ecosystem Based approach to PAs - recognizing connections

Ecosystems and species do not recognise political borders, which were usually defined for historical and geo-political reasons, without reference to ecological functions or processes. Protected areas that are established and managed across borders can therefore provide an important tool for coordinated conservation of ecological units and corridors. An example is the Sundarbans mangroves shared by India and Bangladesh.

To be effective, systems or networks of protected areas need to incorporate the full representation of species and ecosystems, and should take into account representation, replication, and connectivity of coastal areas (McLeod and Salm 2006). In designing site boundaries, it is also important to consider both the adjacent ecosystems that may be tightly linked to mangroves, and also the location and influence of factors beyond the sites boundaries, which are likely to impinge on mangrove survival and productivity. Management approaches also need to incorporate wider areas - protected areas alone will not be enough to secure the future of mangroves, and they need to be built into wider planning regimes. Better recognition of the values of the full range of goods and ecosystem services derived from mangroves may provide the needed impetus for further implementation or improvement of protected areas that incorporate mangrove habitats.

The three basic elements necessary in a more holistic approach to protected areas are:

- **Core wild areas** that contain wild undomesticated plant and animal communities, and the habitat and site requirements needed for their survival

- **Buffer zones** adjacent to core areas where human communities manage land and resources in such a way as to minimize negative impacts on core areas

- **Corridors** that link core areas and buffer zones in a way that allows for plant and animal migrations and provide possibilities for changes e.g. those brought about by climate

**International designation**

Some of the internationally recognized protected area designations applicable to mangroves include:

- **RAMSAR Sites** (Convention on Wetlands of International Importance especially as Waterfowl Habitat, Ramsar, Iran, 1971) is intended to provide a framework for national action and international cooperation for the conservation and wise use of wetlands and their resources.

- **UNESCO Man and Biosphere reserves**. Biosphere reserves are areas that are recognized by the UNESCO’s program on MAB aimed to achieve a sustainable balance between the goals of conserving biological diversity, promoting economic development, and maintaining associated cultural values. These sites are not legally binding and typically zoned with core areas where protection is paramount, and with important buffer and transition areas where human populations reside. They provide international recognition. Designation gives an international profile to a site, which also means it
receives closer scrutiny and greater pressure to ensure wise management. At the end of 2008 there were 501 sites in 105 countries, of which 34 (in 21 countries) had mangroves.

**UNESCO World Heritage Convention** (Convention Concerning the Protection of the World Cultural and Natural Heritage, Paris, 1972). This agreement aims to protect places of outstanding universal value, defined more fully as places ‘so exceptional as to transcend national boundaries and to be of common importance for present and future generations of all humanity.

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**Case Study: Matang Mangrove Forest Reserve**

The Matang Mangrove Forest Reserve in the State of Perak, Malaysia, is arguably the best example of a sustainably managed mangrove ecosystem and demonstrates that an effective balance can exist between the harvest of natural resources and conservation. This reserve, established in 1902, covers an area of about 500 km² making it the largest area of mangroves in Peninsular Malaysia. Approximately 73% is considered productive forest while the remaining portion is classified as non-productive or protected. The existing management plan regulates forestry, fishing, and aquaculture activities and only non-destructive practices are permitted. Harvesting of mangrove timber for poles, firewood, and charcoal production, occurs on a 30 year rotation cycle (Chong 2006). Selective felling is carried during year 15 and year 20 and then a final clear-felling occurs during year 30. When necessary, re-vegetation programmes are implemented two years after the final felling. The annual value of charcoal between 2000 and 2009 was estimated to be RM 27.2 million (equivalent to approx. US$ 8.9 million) while the annual value of poles was estimated at RM 2.6 million (equivalent to approx. US$ 847 thousand). Fisheries in the Matang Mangroves are also an important contributor to the Malaysian economy. Fish cage and cockle aquaculture are allowed, and cockle farming is estimated to have an annual market value of RM 32.45 million (equivalent to approx. US$ 10.7 million). Most of the natural resources obtained from the forest are exported to markets in the states of Selangor, Penang, and Kedah. This case provides evidence that mangrove forests can be conserved and enjoyed while still providing reliable long-term but reasonably high economic return for local and larger communities. It shows that when well-managed, mangroves can ensure sustainable yields of products (numbers are from the Malaysian Timber Council 2009).
3.3 Restoration Tools and Silviculture

Restoration and Afforestation
Restoration and afforestation are viable and widely used management options to recover lost or establish new mangrove forest. While avoiding loss remains the lowest cost and highest benefit route to mangrove conservation and sustainable use, mangrove restoration has been widely practiced around the world. The term restoration (or rehabilitation) is used where mangroves are returned to areas where they previously existed, or where they remain, but are in a degraded state. The term afforestation is used when mangroves are planted in areas where there is no evidence of prior existence. Arguments for restoration vary, but most center on the restoration of ecosystem services, including coastal protection, fisheries enhancement and the provision of timber and fuel wood. By contrast, restoration solely for biodiversity enhancement remains rare. A wide variety of restoration techniques have been developed, but the most critical point is to fit restoration efforts with the local physical and ecological settings, selecting the right species and right locations, and ensuring that land tenure is secure. While there have been failures (Primavera and Esteban 2008, Samson and Rollon 2008), mangrove restoration represents the most successful and widely practiced form of ecological restoration in any coastal or marine setting (Field 1996, Lewis III 2005, Twilley and Rivera-Monroy 2005, Lewis III and Perillo 2009). Afforestation has taken place quite widely (Southeast Asia, Florida, the Middle East), and in some cases the results of such afforestation have been dramatic, with large increases in mangrove-associated species, including birds and commercially important fish (Hong 2004).

Sustainable Silviculture
Sustainable mangrove silviculture (i.e. the planting, management and harvesting of mangrove trees) has been practiced since the 18th century in Southeast Asia (Saenger 2011). Such sustainable management involves establishing formal forestry practices and combining them into a system which functions based on sound ecological principals, careful planning and historical knowledge of the ecosystem being managed (Saenger 2002). Mangroves are dynamic systems highly capable of adapting to changes in their environment when properly managed and maintained in a healthy, resilient state.

With this management style conflicting stakeholder objectives can lead to poor compliance with management initiatives, such as management for timber production versus shoreline protection (Macintosh and Ashton, 2002). For this reason, when designing a management plan, the unique characteristics of the area, a history of the ecosystem, how it is being used, and the specific challenges being faced, all need to be taken into consideration. The best examples of Silviculture revisit these plans to promote effective regeneration, minimize illegal harvesting and to facilitate land tenure arrangements (Vannucci 2004).
3.4 Communication, Education and Public Awareness

Introduction
Given their considerable value, there is rarely any social or economic justification for the loss and degradation of mangroves; on the contrary there are powerful arguments for mangrove conservation and restoration. A critical challenge for those working in the fields of forestry, fisheries and the environment is to communicate these values and to ensure that public and political bodies are fully informed of the consequences of mangrove loss.

Greater knowledge and awareness about mangrove ecosystems and their value is a pre-requisite to increased stakeholder participation and engagement. One of the causes of their ongoing degradation and loss is the lack of understanding and awareness of the value of mangrove ecosystems among various groups of people including policy makers, officials, developers and local people. A major challenge for many working in the fields of mangrove management is to ensure that the public is fully informed of the unique features and value of mangroves as well as the potential consequences of their loss. There are many ways that public outreach could be improved.

In most countries there is considerable scope for improving public understanding and appreciation of the value of mangrove resources and the benefits that can be derived from them. This awareness should form part of the formal educational system but should also be offered to the general public, decision-makers and local people. General awareness can be enhanced through public media campaigns and educational programmes. Where opportunities exist, demonstration sites, boardwalks, interpretive centres, and other activities that bring people into direct contact with mangroves, should be created to encourage local community involvement and increase awareness. Awareness-raising among all stakeholders is an important aspect of any conservation effort involving mangroves. It is also important to have good capacity-building and an effective institutional mechanism that co-ordinates the activities and objectives of all government agencies involved with mangrove management.

Another major cause of inadequate protection and management of mangroves is the shortage of technical capacity at different levels and in different groups. Overall there is a scarcity of mangrove specialists in scientific and management institutions, law enforcement agencies and local communities. There is also a lack of exchange of knowledge and experience between professionals and coastal dwellers. It is essential that technical, legal and financial capacity for mangrove management is strengthened at various levels. Training and education programs need to be targeted specifically at either mangrove managers or professionals, local communities or at central and local government bodies. Priorities for training should be based on local needs and appropriate institutions and courses should be identified on a country-by-country basis. Besides training on specific management tools and techniques, there is also a need to develop capacity to assess mangrove vulnerability and responses to
climate change, and to measure mangrove carbon fluxes so that adequate adaptation strategies can be developed.

Improved capacity and awareness at decision-making levels will lead to informed decisions and better political support, hence more resources. Often projects are not funded or necessary support is not given to management projects because the decision makers are unaware of the magnitude of the problem.

**Designing communication, education and public awareness (CEPA) programmes**

The nature of CEPA programmes can be significantly influenced by factors such as resource availability and the nature of the stakeholders. Therefore, a variety of techniques may be necessary to achieve your communication goals. It is therefore important to take a systematic approach to designing the programme.

**You must:**

- Decide on the central message and objective of your campaign
- Define the target audience
- Choose appropriate communication tools

**Designing a Public-Awareness Raising Campaign**

**Deciding what to raise awareness about**

In designing an effective public-awareness campaign, you must decide what it is that you want to raise awareness about and whom you are addressing the awareness campaign toward.

Some examples of objectives are:

- Disseminate information on Mangrove Ecosystems to improve general understanding of the issue
- Increase awareness of threats
- Encourage stakeholders to take a specific action
- Build support for the use management options
- Motivate people to participate in programmes and activities

**Defining the target audience**

It is vital to specify the target audience for a campaign. This may range from policy makers to school children. The audience type will indicate the best approach to be taken, the nature of the message to be sent and the most effective communication channel.

The list below is indicative of the various types of groups that can come under the broad classification of target audience.

- The general public
- Schools
- Focus stakeholders (e.g. fishermen, wildlife groups, naturalists and others)
- Industry
- Policy makers
Use of appropriate communication tools
The following are a general list of points to consider when promoting messages:
• Formulate a clear message, using simple and easy to understand language
• Use catchy phrases and eye-catching logos.
• Use flagship species or pathways as much as possible to catch attention
Flagship cases can be used to highlight the issue of an endangered species that people value, an economic cost to the ‘average person’, or a health risk to children etc.
• Use consistent messages that not only educate but also motivate changes in behaviour.
• Focus on the solution rather than the problem
• Focus on the values that need to be protected
• Remember to be sensitive to cultural values and perceptions

Many different target groups need education to aid in preventing IAS:
- Politicians - Fishing/mariculture industry
- Scientific community - Shipping community
- Coastal community - Educators
- Port & maritime authorities - General public

Communication Tools
Using the right tool or a combination of tools will result in a better outcome. There is a wide range of tools that can be used effectively with different target groups.
• Mass media such as television, newspapers, radio can reach large numbers of people across a very broad spectrum
• Information in the form of posters, flyers, brochures in areas like pet shops, malls, grocery shops, market places, bus stations, train stations, airports reaches the particular audience that travels or shops in those places.
• Presentations at conferences and related meetings generally target high-level audiences such as scientists and planners
• Lectures at schools using a variety of techniques depending on the age group targeted
• Displays at aquariums or science fairs reach both the general public and target groups (eg. pet owners)
• Community outreach projects. Either creating a new project or combining efforts with an existing one. Outreach projects will use a combination of tools to effectively reach their target audience.

Designing Communication Tools
A poster should engage stakeholders and help get the main points across to as many people as possible.
• A good poster has a clear message, is clearly visual and can be easily read from at least two meters away.
**Remember**

- Choose your message; remember to focus on this message through the poster
- Headings should contain key points, use short sentences and catchy phrases
- Use images and text to support ‘the message’
- Balance the text with images
- Use 2-3 colours
- The audience shapes your poster

Know your audience, and aim the messages at them. Different audiences require different levels of information.
- Remember to leave contact information
- Plan, Draft, Edit and Consult
3.5 Community-based Management, Property Rights and Tenure Issues

3.5.1 Overview

Community-based Management (Reviewed in Datta et al. 2012)
Participation of local user communities is extremely important for the conservation and management of mangrove resources. Community-based mangrove management (CBMM) is prevalent mainly in South and Southeast Asian countries as these were once the most damaged areas caused by widespread destruction of mangroves. Few countries of East Africa, Central America, and South America now have also initiated CBMM, replacing the earlier government controlled management approaches. In some countries, such as Thailand, communities have sole rights to extract mangrove resources and in such cases management is truly community led. However in other countries such as India, the approach to management is more mixed; the state government and village communities share rights to use the mangrove and therefore jointly manage it. Conservation and management of any natural resource will be successful on a long-term basis only when people’s participation in decision-making and civil society awareness is promoted.

Property Rights and Tenure Issues
Rights of ownership, access and use of mangrove forests and land must be explicitly defined, and widely accepted if management plans are to have any chance of success. Ill-defined property rights or overlapping authority over mangrove ecosystems by multiple state agencies, communities or individuals, can lead to conflicts among stakeholders in any location, and can exacerbate the deterioration of mangroves. Many original (indigenous) communities living in tropical coastal zones across the world have traditional rights to mangrove land and depend on mangroves for subsistence. Traditional customary rules and regulations regarding forest resource use evolve and are embedded within their social structure. However, when these rules and regulations are not recognized by the governing state, the result is tension between local communities and official institutions. Where they do not have any legal title to the land other than traditional de facto rights, local people are often displaced by centralized decisions that lead to the development, reclamation and clearing of mangrove habitats. Equitable use, access and tenure should support benefit-sharing, and should provide a secure and stable setting for the development of ecosystem service payments.

3.5.2 WIO Context

For millennia, communities in the WIO have depended on mangroves to sustain their livelihoods. The level of dependence has largely been at subsistence level although commercial exploitation has not been excluded. One critical consideration in addressing community dependence on natural resources
e.g. mangroves is their involvement in management which will also determine access their access to such resources.

Mangroves naturally occur in riparian land and as such are managed through various management regimes in the different countries of the WIO region. In some countries, mangroves are managed directly by the state through relevant government agencies especially those dealing with forest management; while other have embraced a devolved management structure/approach where communities or local governance agencies are allowed by national governments by delegation to manage mangrove forests within their area of jurisdiction. For instance, in Kenya up to 2005, mangroves and forests in Kenya in general were managed through a top-down approach where government directly managed forests through policing. However, subsequent to the review of the Forest Act, now communities are allowed to manage forests adjacent to them through the formation of community forest associations (CFAs), thus providing a legal framework for Participatory Forest Management (PFM). Under this framework, communities are allowed to develop management plans and forest agreements as legal instruments through which the Kenya Forest Service (KFS) then delegates the management of the forest block in question to such a CFA. KFS still remains with the overall oversight role over forest management.

This delegated governance structure has enhanced community access to forest resources and encouraged development of alternative livelihoods in mangroves e.g. eco-tourism, integrated aquaculture and more recently, carbon projects with the Mikoko Pamoja at Gazi Bay being the first global example of a small scale mangrove carbon project.
4.0 Mangroves in a Changing Climate

4.1 Climate Change Impacts on Mangroves – Overview

As inhabitants of the harsh inter-tidal zone, mangroves have evolved to deal with a wide variety of environmental changes such as daily fluxes in temperature, water, salinity and oxygen availability. The geologic records provide evidence that mangroves have experienced many chronic disturbances as a result of sea-level fluctuations (Lessa and Masselink 2006, Woodroffe 1990). However climate change will pose unprecedented natural challenges to these unique ecosystems.

Below, we summarize some of the predicted impacts of climate change on mangrove ecosystems (adapted from Van Lavieren et al. 2012). We emphasize the impact of sea-level rise as this is projected to be the greatest climate change threat to these systems.

Changes in temperature: Global temperatures increased by 0.74°C (+/-0.18°C) between 1906 and 2005 and most models predict rises of 2°C to 4°C within the next 100 years (IPCC 2007).

Impact: Changes in atmospheric and sea surface temperatures may result in expanded latitudinal limits for some species, alteration of community composition and increases in photosynthesis, respiration, litter, microbial decomposition, floral and faunal diversity, growth and reproduction, but declining rates of sediment accretion (Field 1995, Alongi 2008). At local and regional scales, changes in weather patterns may induce changes in the salinity regime and community composition as a result of salinity changes, and a change in primary production if the ratio of precipitation to evaporation is altered (IPCC 2007).

Changes in atmospheric carbon dioxide (CO₂): CO₂ levels increased from 280 ppm in 1750 to nearly 380 ppm in 2005 (Solomon et al. 2007) and are presently almost 400 ppm. Despite large variations, all models predict a further increase in CO₂ levels by the end of the century, with some predicting a doubling or even trebling of today’s level.

Impact: Responses to this change will be difficult to predict, but rates of photosynthesis, salinity, nutrient availability and water-use efficiency will likely change (Ball et al. 1997). There will likely be little or no change in canopy production, but species patterns within estuaries are likely to change based on species-specific responses to the interactive effects of rising CO₂, sea-level, temperature, and changes in local weather patterns (Alongi 2002, 2008). Elevated CO₂ concentration could alter competitive abilities, thus altering community composition along salinity-humidity gradients (Ball et al. 1997).

Changes in sea-level rise: Mean global sea-level rose 17cm in the 20th century (IPCC 2007). In 2007, the IPCC predicted that mean global sea-level may rise a further 18-79 cm by 2100 (IPCC 2007), however,
some of the latest research suggests a rise up to 1m or more (Jevrejeva et al. 2010, Nicholls and Cazenave 2010).

**Impact:** This is likely the greatest of challenges facing mangroves as a result of climate change (Gilman et al. 2008). In the past, mangroves responded to sea-level rise by growing upwards in place or migrating landwards (Alongi 2008). Mangroves are able to increase their elevation by making peat from decaying litter and root growth, and also by trapping sediments (McLeod and Salm 2006). As sea-level rises and wave energy causes their seaward margin to erode, mangroves can also move landward if space is available and conditions are suitable for new seedlings to establish and grow on the landward edge (Gilman et al. 2007). Together, these processes help mangroves maintain their elevation relative to the sea-level.

There are observations of mangroves that shifted inland 1.5 km over the course of 70 years (Ross et al. 2000).

The ability of mangroves to migrate landward is also determined by local conditions, including the presence of infrastructure (e.g. seawalls, dikes, urban developments) and the topography of the area (McLeod and Salm 2006). For example, coastal developments such as sea defences “fix” the intertidal zone and prevent intertidal habitats from expanding landward – a process referred to as coastal squeeze. Therefore, even in cases where mangroves may be able to migrate landward at an adequate pace, they could be hindered by the unavailability of suitable substrates due to human encroachment and land development at coastal boundaries (Spalding et al. 2010). To enable landward migration, in some areas, coastal retreat may be necessary.

Generalized responses of mangrove ecosystems experiencing relative sea-level rise: a- without landward barriers, where mangroves can migrate inland; b- where such migration is prevented by barriers
(Source: Spalding et al. 2010)
While there is considerable variation in the current responses of mangroves to rising sea-level, in the majority of sites studied, these forests are not adapting at an adequate pace (Cahoon et al. 2006). Adaptation to local factors, such as changes in tidal range and sediment supply, will likely be species dependent (Alongi 2002, 2008). When sea-level rise is too rapid for landward migration or soil accretion by mangroves, the soil surface submerges and the edges of the remaining wetlands are exposed. This leads to erosion, as well as the release of carbon deposits stored in the soil (Chmura et al. 2003).

**Changes in intensity and frequency of storms:** Both the number and intensity of very strong cyclones (typhoons and hurricanes) will increase (IPCC 2007).

**Impact:** The level of impact will be proportional to the strength, frequency, size and duration of storms. Impacts include defoliation, tree up-rooting mortality, and increased stress from altered mangrove sediment elevation due to soil erosion, deposition, and compression (Smith et al. 1994, Cahoon et al. 2003). Recovery from storm damage can be very slow or not occur at all. Large storms have caused mass mortality in some mangrove forests (Cahoon et al. 2003, Armentano et al. 1995).

**Changes in precipitation patterns:** In the 20th century significantly increased precipitation has been observed in eastern parts of North and South America, North Europe and North and Central Asia, while drying has been observed in the Mediterranean, southern Africa, the Sahel and parts of southern Asia (IPCC 2007). It is very likely that in the 21st century the amount of precipitation will increase at high-latitudes and decrease in most subtropical land regions (IPCC 2007). It is also very likely that heavy precipitation events will become more extreme (IPCC 2007). El Nino has also been compounded with a new phenomenon called the Indian Ocean Dipole (IOD) operative within the Indian Ocean rim (Saji et al. 1997, Overpeck and Cole 2007). A 115-year coral record from Kenya has been found to preserve the history of rainfall anomalies in East Africa in relation to global warming-induced Indian Ocean Dipole (IOD) variability (Nakamura et al. 2009). The IOD phenomenon which has become more frequent in recent decades has weakened the ENSO-monsoon relationship, thus having a more profound influence on climate variability in the region. The floods and droughts which have recently been experienced in the region and normally alternate between the Eastern and Western Indian Ocean are thus significantly IOD driven.

**Impact:** Regional and local patterns of growth and distribution may be affected (Field 1995, Ellison 2000). Increased intensity of rainfall events is likely to influence erosion and other physical processes in catchments and tidal wetlands. Increased rainfall may increase diversity and enhance growth and coverage via colonization of previously un-vegetated areas. Reduced rainfall may lead to reduced diversity and productivity of mangroves and increases in salt marsh and salt flat areas (Smith and Duke 1987). The most immediate indirect effects of climate change on mangroves are massive sedimentation and flooding, which have already had widespread devastation although these impacts have not been well documented in the region (Bosire et al 2006).
Conclusion
Overall, some highly adaptable mangrove plant species will survive and perhaps even thrive with the projected climate changes, but many, likely, will not (Alongi 2008). The direct effects of climate change alone may lead to a global loss of over 10-15% of total mangrove area (Alongi 2008). In consideration of the current rates of deforestation (losses of 1-2% total area per year, Alongi 2002), it is not unreasonable to predict that mangrove forests may all be gone within the next 100 years (Duke et al. 2007). Loss of these ecosystems will have serious implications for the well-being of societies which depend on them for goods and services.

A Scenario of the Impact of Climate Change in Shifting Mangrove Fisheries

We have seen that rising sea level due to climate change will definitely have consequences on mangrove ecosystems such that some parts of the mangroves will either shift where conditions allow or succumb. In both scenarios, we are concerned about what will secondary consequences to related to fisheries because mangrove are a nursery and feeding ground for resident and visiting fauna. Mangroves and estuaries are not only nursery and feeding grounds for fish but are also where freshwater and seawater converge especially in estuaries and deltas, creating enabling environments for new breeds more adapted to these environments. With the inward transgression estuaries and mangroves that they support, fish with may move inward in proportion to specific ecosystem services available to them. Where mangroves are completely destroyed, mangrove fisheries will diminish in response. Those people dependent on these fish for their livelihoods will subsequently suffer from the shortage of food and income, and become viciously subjected the poverty trap.
4.2 Mangroves of the WIO and Climate Change

Mangroves of the WIO regions are not spared the impacts of climate changes as described previously and their responses will be largely similar. However, the patterns may vary depending on the geomorphological settings in which they occur. Climate change stressors that have been mostly observed to impact on mangrove of the WIO include prolonged droughts, sea level changes, and increased storm intensity that result into flooding. Climate change related factors such as sea level rise and increased sedimentation have affected the fringing mangroves in Kenya, Tanzania, Mozambique and Madagascar (FAO, 2005). These stressors exacerbate the non-climate destruction by contributing to mangrove dieback, and altering mangrove ecosystems that support fisheries, coastal health, and flood control. There are specific examples already following the elevated intensity and frequency of tropical storms and floods like those of 1997/98 El Niño which caused massive mangrove mortality in the major river estuaries and deltas in the region with reports from Tanzania in the Rufiji (Erf temeijer and Hamerlynck 2004), Kenya in Tana (Wieczkowski 2008), Mozambique in the Zambezi (Barbosa et al. 2001) and South Africa (Forbes and Cyrus 1992).
4.3 Mangroves and Carbon

Even though mangroves, coastal marshes, and seagrasses have relatively small total area, the carbon beneath these habitats is considerable (Murray et al. 2011). When the whole ecosystem is considered, mangroves have been estimated to contain on average 1,023 Mg C ha$^{-1}$ (1Mg = 1,000 kilograms), which is over three-fold more carbon per unit surface area compared to boreal, temperate and tropical upland forests (Donato et al. 2011). Mangroves also have more carbon per hectare than other blue carbon habitats (saltmarshes and seagrasses) (Murray et al. 2011).

Carbon sequestration by plants is known as green carbon. This term refers to the process whereby carbon is removed from the atmosphere through photosynthesis, and then stored in the biomass and soil of the capturing ecosystem (e.g. forest land, agricultural lands, plantations and pasture land) (Nelleman et al. 2009). Green carbon has mainly been considered in terrestrial systems (Nelleman et al. 2009). It has been recognized that maintaining and improving the ability of forests to absorb and sequester carbon is an essential component of climate change mitigation (Chhatre and Agrawal 2009). As a result, green carbon strategies are increasingly used as a tool in international management policies and plans.

A carbon sink is “any process, activity, or mechanism that removes a greenhouse gas, an aerosol, or a precursor of a greenhouse gas or aerosol from the atmosphere” (IPCC 2007). The coastal vegetative habitats of the ocean are excellent carbon sinks. The absorption and burial of carbon by oceans and oceanic systems, including vegetative habitats (mainly mangroves, salt marshes and seagrasses) is called, “blue carbon” (Nelleman et al. 2009).

Mangroves are one of the most carbon-rich tropical forests and have extremely high carbon storage rates (Donato et al. 2011).

Let’s now explore how coastal ecosystems, particularly mangroves sequester and store carbon.

The carbon sequestration process occurs as a result of the autotrophic nature of coastal ecosystems. Coastal ecosystems, including mangroves, remove CO$_2$ from the atmosphere through photosynthesis, return some to the atmosphere through respiration and oxidation, and store the remaining carbon in two pools: living biomass (both aboveground and belowground vegetation) and soil organic carbon (Murray et al. 2011).

Blue carbon (including mangrove) sequestration and storage involves three major components (Sifleet et al. 2011):

1) **Annual sequestration.** The annual sequestration rate is the quantity of CO$_2$ removed from the atmosphere and trapped in natural habitats each year (Sifleet et al. 2011). In a mature mangrove system this refers to the yearly flux of organic material transferred into anaerobic soils, where it cannot be changed back to CO$_2$ and released to the atmosphere (Sifleet et al. 2011). Mangroves can sequester
carbon at an average rate at or below 7 Mg of CO₂e (1Mg= 1,000 kilograms, CO₂e = carbon dioxide equivalent) per hectare, per year (Sifleet et al. 2011). While this estimate is comparable to the sequestration rate for other coastal systems (seagrass and saltmarshes), it is more than three times greater than global rates reported for tropical forests (Lewis et al. 2009).

2) Carbon stored in living biomass, both above- and belowground. Mangroves store carbon in both above- and belowground biomass. Aboveground biomass comprises leaves, stems, flowers, branches, and trunks, while belowground biomass includes mainly roots and associated fauna and flora (Sifleet et al. 2011). Mangroves contain on average between 300 and 1,000 Mg CO₂e per hectare in living biomass (Sifleet et al. 2011). This range is much higher than estimates for both seagrasses and saltmarshes (Murray et al. 2011).

3) Soil carbon stocks. This refers to the carbon in the column of organic soil lying beneath coastal habitats as a result of prior sequestration (Sifleet et al. 2011). This stock is determined by both the soil carbon density and soil depth (Sifleet et al. 2011). The largest store of carbon in coastal ecosystems lies within the soils (Sifleet et al. 2011). Approximately 49-98% of the carbon stored in the entire mangrove system is stored in the soil (Murray et al. 2011, Donato et al. 2011). Soil depth in mangrove varies from 0.5m to over 10m (Sifleet et al. 2011). Carbon that is sequestered in the soil of mangroves, salt marshes and seagrass meadows can remain stored there for thousands of years (Mateo et al. 1997). This is one of the most important aspects of mangroves and carbon sequestration; it is long term carbon sequestration. In many mangrove forests, soils have been building constantly for 5,000 years or longer (Crooks et al. 2011). Most estimates of carbon soil stocks for mangroves fall between between 800 and 3,000 Mg CO₂e per hectare (Sifleet et al. 2011).

Why do mangroves have more carbon than most other ecosystems?
Unlike terrestrial forests which tend to plateau in their carbon burial capacity (Schlesinger and Lichter 2001), both above- and below-ground carbon storage, as well as the rate at which carbon sequestration occurs, increase with time in mangrove ecosystems (Alongi 2011, Alongi 2009, Chmura et al. 2003). Mangroves are very dynamic systems. Storage of carbon in sediments continues to increase over time because mangrove sediments increase in volume in response to rising sea-levels (McKee et al. 2007). Mangroves continue to store carbon in their sediments from riverine deposits and they also trap organic carbon from tidal movements of water. For these reasons, mangroves have higher concentrations of carbon per unit area than most other ecosystems.

Even though mangroves, coastal marshes, and seagrasses have relatively small total area, the carbon beneath these habitats is considerable (Murray et al. 2011). When the whole ecosystem is considered, mangroves have been estimated to contain on average 1,023 Mg C ha⁻¹ (1Mg = 1,000 kilograms), which is over three-fold more carbon per unit surface area compared to boreal, temperate and tropical upland forests (Donato et al. 2011). Mangroves also have more carbon per hectare than other blue carbon habitats (saltmarshes and seagrasses) (Murray et al. 2011).
Conclusion
Mangroves store large amounts of carbon for thousands of years, making them highly effective carbon sinks. Due to this unique capacity, disturbance to mangrove habitats has the potential to release large amounts of GHGs. In the next section, we will explore what happens to the carbon in mangrove forests when these ecosystems are degraded or converted for other uses.
4.4 Mangroves and Climate Change Mitigation

There are substantial stores of carbon beneath mangroves, seagrasses and saltmarshes (Murray et al. 2011) which is at risk of future release due to anthropogenic activities. The total stored carbon stock at risk of release is calculated as the average amount of soil carbon held in the top meter plus the biomass (Murray et al. 2011). For mangroves, this number has been estimated at 24 billion tCO₂e (Murray et al. 2011). The carbon stored in a typical hectare of mangroves could contribute as much to GHG emissions as three to five hectares of tropical forest, if released into the atmosphere (Murray et al. 2011).

Mitigation refers to human interventions to reduce the sources of or enhance the sinks for GHG (IPCC 2007). Halting current rates of mangrove deforestation would lead to mitigation of approximately 170 – 490 million tCO₂e per year (Murray et al. 2011). When seagrasses, saltmarshes and mangroves ecosystems are considered together, the total blue carbon mitigation potential is between 300-900 million tCO₂e (Murray et al. 2011). To put this estimate into perspective, this is approximately equal to the annual anthropogenic CO₂ emissions (except for land use change) for Poland and for Germany, respectively¹. Potential emissions from mangrove loss make up approximately 55% of this total carbon stock at risk (Murray et al. 2011).

1. Emissions are for 2007 (Boden et al. 2010).

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4.5 Climate Change Frameworks and Policies

Tropical deforestation is estimated to contribute up to 18% of global greenhouse gas emissions (IPCC 2007) – the third largest source of anthropogenic greenhouse gas emissions after energy supply and industrial activities. A set of international policies known as ‘Reducing emissions from avoided deforestation and forest degradation’ or REDD+ were introduced during the 11th session of the Conference of the Parties (COP11) to the United Nations Framework Convention on Climate Change (UNFCCC), in December 2005, and won support from almost all Parties, intergovernmental organizations and non-governmental organizations. REDD+ is concerned with both reducing emissions and enhancing carbon stocks through actions that address deforestation, forest degradation, forest conservation and sustainable forest management. The basic idea behind REDD+ is simple; countries that are willing and able to reduce emissions from deforestation and forest degradation should be compensated for doing so.

As signatory to Kyoto Protocol of UNFCCC many countries in the region stand to benefit from trading in carbon emissions reduction credits (CERS) - through both compliant and voluntary carbon markets. Already, Kenya has submitted her REDD Readiness Preparation Proposal (R-RPP) that stipulates to raise the current forest cover in Kenya to 10%; thereby contributing to climate change mitigation as well as improving the livelihoods of communities dependent on the forests through the multiple benefits such as carbon credits. Similar initiatives have been made by Tanzania, Madagascar and Mozambique.

4.5.1 Carbon Markets and Carbon Financing Options

Carbon credits are a tradable certificate or permit representing the right to emit one tonne of carbon dioxide equivalent (measured as tCO\textsubscript{2}e). Under the Kyoto Protocol, countries are encouraged to decrease carbon emissions of CO\textsubscript{2} and generate carbon credits for sale. Carbon credits can be sold to buyers who either voluntarily (such as in voluntary carbon markets) or under regulations (such as in the compliance market), will purchase them to compensate for, or offset their own CO\textsubscript{2} emissions. So, while at an individual level, some countries (usually developed) are producing excessive GHGs, they can buy the negative outputs from those countries (usually developing) that are actively decreasing their outputs, with the goal of creating an overall global decrease in GHG emissions.

The transfer of carbon credits between a buyer and a seller is a form of emissions trading which creates a carbon market. The flow of emission rights (emissions trading) within the developed world and between the developing and developed worlds have created a global carbon market (Murray et al. 2011). The benefit of emissions trading is that the buyer pays a charge for polluting, while the seller is rewarded for having reduced emissions. Carbon markets create financial incentive to convince the holders of coastal ecosystems to avoid habitat conversion and thus lessen the probability that these ecosystems will change from GHG sinks to sources (Murray et al. 2011).
The potential monetary value of blue carbon activity is the product of the GHG emission reductions and the price received per unit of reductions (Murray et al. 2010). Firstly, the potential blue carbon credit source is identified-in this case, mangroves and their emissions reductions capacity. Secondly, the quantity of CO₂e whose release will be averted through avoiding conversion of mangroves is calculated. To arrive at the total creditable carbon, these avoided carbon emissions are added to the annual carbon sequestration rate of that particular forest area. This sum is then multiplied by expected carbon prices ($/tCO₂e) over a certain time period to arrive at present value estimates of an avoided conversion project ($/tCO₂e/ha/yr). From a financial perspective, conserving a mangrove area will be attractive if the monetary value of carbon payments received for protection is greater than the costs of protection (Murray et al. 2010).

Globally, avoiding mangrove losses has the potential of being economically justified on the basis of avoided CO₂ emissions alone (Siikamäki et al. 2012). However, even if payments for blue carbon are less than the cost of protection (i.e., protection is more expensive), this does not mean that protection should not occur (Murray et al. 2010). Aside from their blue carbon potential, mangroves provide critical ecosystem services to coastal communities. Protection and management of mangroves for their carbon value would also incur biodiversity and socio-economic benefits to these communities and fisheries (Siikamäki et al. 2012). These unpriced services add to the economic value of mangroves and can be used as additional support when marketing mangrove conservation and blue carbon in a global carbon finance scheme (Siikamäki et al. 2012).

Payments for Blue Carbon

Overall, monetary payments for blue carbon can change economic incentives to favor protection of coastal habitats, like mangroves (Murray et al. 2011). In order for this to take place, there needs to be appropriate economic policies and programmes that support such payments and recognize the importance of coastal systems as tools for ecosystem-based climate mitigation.

Let’s review some important activities of the United Nations Framework on Climate Change which are relevant to blue carbon finance.

Overview of the UNFCCC Activities

A logical venue for considering blue carbon payments would be through the United Nations Framework Convention on Climate Change (UNFCCC) process (Murray et al. 2010). Created in 1992, the UNFCCC is an international environmental agreement between countries to stabilize GHG concentrations in the atmosphere “at a level that would prevent dangerous anthropogenic interference with the climate system”*. Towards this end, the UNFCCC created two important mechanisms:

- The **Kyoto Protocol**, a mechanism by which the most developed countries agreed to reduce GHG emissions by approximately 5% below 1990 levels by 2012*. The Kyoto Protocol permitted developed countries to trade emission rights among themselves to meet reduction commitments.
- **Clean Development Mechanism (CDM)**, which allowed developed countries to partner with developing countries and undertake GHG reduction projects to create marketable credits that generate revenue for them and that help developed countries meet their commitments more cheaply.

The UNFCCC encourages its members to support sustainable management, conservation and enhancement of GHG sinks and reservoirs in coastal and marine ecosystems (Crooks et al. 2011). This suggests that it is possible to integrate coastal ecosystems into UNFCCC mechanisms that already exist (Herr et al. 2012). While there are currently no specific mechanisms within the UNFCCC that focus on blue carbon (Murray and Vegh 2012), there are several incentives to support emission reductions and removals from nature-based activities under the UNFCCC which could be broadened to include blue carbon sources, particularly mangroves.

*Below, we introduce some of these initiatives, highlighting the opportunities and challenges to the inclusion of blue carbon systems.*

- **Reducing Emissions from Deforestation and Forest Degradation (REDD)**

  REDD is an initiative which creates financial values for carbon sequestered in terrestrial forests. It provides incentives for developing countries to reduce emissions from forested lands and invest in low-carbon development mechanisms. An offshoot of the program, REDD+ (post-Kyoto: 2013 onwards) will include strategies which go beyond deforestation and forest degradation to include conservation, sustainable management, and enhancement of carbon stocks as part of the incentives. While mangrove forests may already fit within the general REDD framework, soil carbon, which constitutes the vast majority of carbon in blue carbon habitats, is generally excluded from carbon offsets in REDD (Siikamäki et al. 2012). Excluding below ground carbon will undermine the mitigation potential of blue carbon habitats such as seagrasses, which are not currently included in the REDD+ program (Murray et al. 2011). Fortunately, a few countries have already included mangroves in their national REDD+ plans including, Tanzania, Costa Rica, Indonesia and Ecuador (Herr et al. 2012).

  *See [http://www.un-redd.org/](http://www.un-redd.org/) for further information on REDD and REDD+*

- **Clean Development Mechanism (CDM)**

  The CDM is a project-based ‘flexibility mechanism’ that was defined by the Kyoto Protocol (IPCC 2007). Under the Kyoto Protocol, industrialized countries can use the CDM to earn certified emission reductions (CERs) credits by ‘sponsoring’ projects in developing countries which reduce GHG emissions. CERs can be traded and sold to meet a part of emission reduction targets under the Kyoto Protocol (Herr et al. 2012). CDM currently focuses on terrestrial forests, but large-scale and small-scale methodologies for mangrove restoration have already been accepted for inclusion as an afforestation/reforestation (A/R) activity under this agreement (Murray et al. 2011). Unfortunately, this may be a limited opportunity since the proposed qualifying A/R activity is restoration (Murray et al. 2011). Therefore, much larger avoided emissions through protection of blue carbon stocks (including mangroves) would remain outside the mechanism for the time-being (Murray et al. 2011).
• **National Appropriate Mitigation Actions (NAMAs)**

NAMAs refer to a set of policies and actions that countries undertake as part of a commitment to reduce GHG emissions. All national activities aimed at mitigating climate change may qualify as NAMAs. This strategy emphasizes financial assistance for developing countries (Herr et al. 2012). By implementing NAMAs, developing countries can receive international financial support for nationally appropriate climate change mitigation actions (Herr et al. 2012). For example, countries could use blue carbon related NAMAs to explore opportunities to access finance for coastal management activities (Herr et al. 2012).

• **Land Use, Land Use Change and Forestry (LULUCF)**

Countries who have signed onto the UNFCCC are required to create and submit yearly National Inventory Submissions (NIS). These record their GHG emissions from energy use, industrial use, land use, agriculture, waste, and sequestration from land use and forestry (Laffoley and Grimsditch 2009). Within NIS, there is a section entitled Land Use, Land Use Change and Forestry (LULUCF). LULUCF currently accounts for GHG emissions and sequestration from the management of only terrestrial carbon sinks (including afforestation, reforestation, deforestation, changes to soil carbon stocks from land use/land use change, peatland extraction, drainage, soil liming, etc.). As tidal forests, mangroves are includable under the category of “forest” and activities relevant to their use as carbon sinks could be reported (Murray and Vegh 2012). Mitigation achieved either by removing GHGs from the atmosphere or by reducing GHG emissions, can be used by Parties to the UNFCCC as part of their efforts to implement the Kyoto Protocol (Herr et al. 2012).

*Outside of the UNFCCC process, Voluntary Carbon Markets provide an opportunity to support blue carbon activities*

**Voluntary Carbon Markets**

Compliance markets are created and regulated by mandatory carbon reduction agreements such as the Kyoto Protocol. Voluntary carbon markets (VCMs) are not included within regulated trading mechanisms and lie outside of the UNFCCC Framework. These markets enable individuals and countries to purchase carbon offsets on a voluntary basis. In terms of protecting mangroves, VCMs may be more flexible in accommodating related blue carbon restoration and conservation projects. Methodologies for the application of blue carbon projects in VCMs are more developed and could ultimately serve as the basis for the development of regulated market methodologies (Van Lavieren et al. 2012).

Under the VCM the Mikoko Pamoja project in Kenya is already generating carbon credits for mangroves (see the case study below):
**Case Study: Blue Carbon Project - Mikoko Pamoja**

Mikoko Pamoja is a small scale carbon feasibility project in Kenya that aims at enhancing mangrove productivity and integrity; by carrying out activities that benefit local communities and that could be eligible for attracting carbon investment. 


The overall goal of this project is to direct finance to the restoration and protection of mangrove ecosystems in Gazi Bay, Kenya through provision of and payment for mangrove ecosystem services. The intended impacts of the project are to increase the quality and extent of the current forest and maintain and enhance carbon sinks through protection and planting activities. These impacts will generate income for the Gazi Bay community that will be spent on community development projects.

Specific Project activities include:

- Maintaining mangrove nurseries and reforestation of degraded areas
- Delineating and mapping of projected areas
- Determining the carbon storage capacity of Gazi Bay mangroves using GIS and ground-truthing
- Planting *Casuarina* plantations to subsidize mangrove wood
- Payments for ecosystem services – expansion of community fund to support needed projects (e.g., new school buildings)

Starting with an initial 117ha of mangroves, Mikoko Pamoja will generate 3,000t CO$_2$-equivalent of carbon credits that will be sold into the voluntary carbon market; generating approximately US$12,000 for the local community per annum. One-third of the annual carbon income generated through the project used for the rehabilitation and protection of mangroves.

*See below for a diagram of the flow of finances in the Mikoko Pamoja project*
External Buyer of the Carbon Credits

Estimated Income per year is USS 15000 (100%)

Mikoko Pamoja Coordinating Group

3% of income

Group Expenses (Stationery etc)

97% of the Income

Mikoko Pamoja Community Based Organization

25% of the Income

Project Coordinator Salary

33% of the Income

37% of the Income

Group Expenses (Stationery etc)

Projects for Community Benefit. The Expenditure is determined through a community benefit consultation process.

Mikoko Pamoja Work Teams
Nursery establishment
Mangrove policing
Monitoring and Evaluation tasks
4.6 Valuing Ecosystem Services – Concepts and Methods

The Economics of Ecosystems and Biodiversity (TEEB)
The Economics of Ecosystems and Biodiversity (TEEB) initiative helps draw attention to some of the economic benefits of mangrove ecosystems and confirms that the cost of sustaining ecosystem services is lower than the cost of allowing them to dwindle. One study shows that planting and protecting nearly 12,000 hectares of mangroves in Vietnam cost just over US$1 million but saved annual expenditures on dyke maintenance of well over US$7 million (World Disasters Report 2002). TEEB draws together expertise from the fields of science, economics and policy to highlight costs of biodiversity loss and ecosystem degradation. It calls on policy makers to accelerate, scale-up and embed investments in the management and restoration of mangrove ecosystems and for more sophisticated cost-benefit analysis before policy decisions are made.

Importance of Ecosystem Services:
Ecosystems contribute substantially to human well-being. In fact, everyone in the world is completely dependent on Earth’s ecosystems (MEA 2005). Ecosystems are linked to human well-being through the services that they provide. The Millennium Ecosystem Assessment was a global initiative undertaken from 2001-2005 to investigate how changes in ecosystems affect human well-being and to identify actions to enhance the conservation and sustainable use of ecosystems as well as their contribution to human well-being (MEA 2005).

Economic assessments provide some of the most powerful arguments in favour of mangroves management, protection or restoration. Not only are mangroves valuable in their own right, but they are often considerably more valuable per unit area than alternative uses, including aquaculture, agriculture or even tourism.

The Millennium Ecosystem Assessment defines ecosystem services as “the benefits people obtain from ecosystems”.
This assessment recognized four categories of ecosystem services:

Supporting services: Services necessary for the production of all other ecosystem services, e.g., soil formation, nutrient cycling and primary production.

Provisioning services: Products obtained from ecosystems, e.g., food, fresh water, fuelwood, fiber, biochemical and genetic resources.

Regulating services: Benefits obtained from regulation of ecosystem processes, e.g., climate regulation, disease regulation, water regulation, water purification.

Cultural services: Nonmaterial benefits obtained from ecosystems, e.g., spiritual and religious, recreation and ecotourism, aesthetic, inspirational, educational, sense of place and cultural heritage.
Mangroves provide many important ecosystem services:

Let's begin by exploring their **Provisioning Services:**

People derive many natural products from mangroves. These include the following (UNEP-WCMC 2006):

- **Commercial and subsistence fisheries:** Mangroves are critical intertidal habitats for many fishes, mollusks and crustaceans of value to coastal communities. Mangrove fisheries provide food, employment and income to millions of people around the world and thus the importance of this service cannot be overemphasized.

- **Aquaculture:** Mangroves support aquaculture operations for mollusk, fish and shrimp. In some countries, land-based pond farming of fish and crustaceans in former mangrove areas is a centuries-old tradition (Schuster 1952). It is ironic that in recent decades, aquaculture has been the major cause of global mangrove loss (Valiela et al. 2001), because mangroves provide critical support to aquaculture in the form of seed, broodstock and feed (Rönnbäck 1999). Small-scale, sustainable mangrove-aquaculture operations still exist in some areas.

- **Food items,** including parts of mangrove themselves (e.g., mangrove fruit) and honey

- **Building materials for construction,** energy and industry such as wood, leaves, tannins and nypa palm

- **Raw materials for traditional medicines and genetic resources**

Mangroves provide the following **regulating services:**

- **Climate regulation:** Mangroves play an important role in climate regulation because they capture and store large amounts of carbon (Murray et al. 2011, Donato et al. 2011, Nelleman et al. 2009). The carbon sequestered and stored in mangroves and other marine and coastal systems is referred to as ‘Blue Carbon’ (Nelleman et al. 2009). The importance of mangroves as Blue Carbon habitats and their potential as a tool for climate change mitigation is being increasingly recognized by governments, intergovernmental organizations and mangrove advocacy groups.

- **Erosion regulation:** Vegetative cover aids soil retention (MEA 2005). By diminishing the energy of incoming waves, mangroves prevent sediments from being washed away and reduce shoreline erosion (Mazda et al. 2007, Thampanya et al. 2006). For example, a study has shown that in areas where mangroves form extensive stands in the Gulf of Thailand, it seems that net erosion has been prevented (Thampanya et al. 2006).

- **Water purification** - Mangrove vegetation is highly productive and filters nutrients and pollutants from the water (Kathiresan and Bingham 2001). Being situated between the land and the sea allows them to intercept land-derived nutrients, pollutants, and suspended matter before such contaminants reach coastal environments (Rivera-Monroy and Twilley 1996, Tam and Wong 1999).

- **Protection from natural hazards** – Mangroves play an important role in shoreline protection under normal sea conditions and during tropical storms and hurricanes (UNEP-WCMC 2006). This is because the presence of mangroves can attenuate waves and reduce the impacts of
storm surges (McIvor et al. 2012ab). The complex structure of mangrove trees, particularly their extensive root systems can diminish the energy of incoming waves and lessen the risk of flooding to communities which live behind mangroves (McIvor et al. 2012a). As such, they can serve as a coastal buffer, protecting communities from natural hazards.

Mangroves provide the following supporting services.

- **Nutrient cycling** – Mangrove plants are efficient at conserving and recycling nutrients (Kristensen et al. 2008). These trees produce large amounts of leaf litter and the decomposition of this litter contributes to the recycling of nutrients within the mangrove as well as adjacent habitats (Kathiresan and Bingham 2001).

- **Nursery Habitat** – Mangroves not only act as nurseries for fish and crustaceans which reside in the mangrove for the entirety of their life, but also species which are found as adults in offshore habitats. Several offshore species which use mangroves as nurseries are of particular economic importance. For example, offshore shrimp fisheries in Northern Australia, the Guianas, Mexico and Borneo are major economic activities and the species which comprise the bulk of catches are either mangrove dependent or benefit greatly from the presence of inshore mangroves (Spalding et al. 2010).

**Cultural Services** encompass a range of nonmaterial benefits that people derive from ecosystems. These include opportunities for spiritual enrichment, reflection, recreation, cognitive development and aesthetic experiences (MEA 2005).

- **Tourism and recreation** – Mangroves have gained increasing popularity as sites for ecotourism (Spalding et al. 2010). The creation of boardwalks through these forests has made them more accessible to visitors. Popular tourism activities include boat tours, wildlife watching and kayaking.

- **Spiritual** – Mangroves may contain sacred sites of worship or be the location of culturally significant rituals. *Students should refer to Unit 6- Mangroves and People for specific examples from around the world*

**Connecting ecosystem services to human well-being**

*Let’s have a look at how all of these services connect directly to human well-being.

The image below is adapted from the Millennium Ecosystem Assessment 2005. It shows the strength of linkages between categories of ecosystem services and the various components of human well-being. It also depicts the extent to which it is possible for socioeconomic factors to mitigate this linkage – for example, if it is possible to purchase a replacement for an ecosystem service the potential for remediation is high.*
Connecting Ecosystem Services to human well-being

The image above is adapted from the Millennium Ecosystem Assessment 2005. It shows the strength of linkages between categories of ecosystem services and the various components of human well-being. It also depicts the extent to which it is possible for socioeconomic factors to mitigate this linkage – for example, if it is possible to purchase a replacement for an ecosystem service the potential for remediation is high.
It should now be evident that ecosystem services enhance human well-being substantially. Therefore, the loss of these ecosystems entails the loss of these services and often a reduction in human well-being. Another way of thinking about this relationship is that humans derive utility from ecosystems, i.e., the services they provide are ‘useful’ to us. Because they are useful to society, they contribute to society’s welfare. Welfare is an economic measure of society’s level of “happiness”. In conducting an economic assessment, what we want to measure are changes in society’s welfare associated with the loss or gain in environmental goods or services. These changes in welfare represent the benefits or costs to society as a result of a change in environmental service provision.

**What is an economic valuation and why is it useful?**

Maintenance of ecosystems requires effort and investment of financial and human resources. This is because ecosystems provide a basis for alternative economic activities such as agriculture after land conversion, water supply and hunting. These activities cannot always be undertaken at the same time and conflicts of interests arise. For example, a mangrove area cannot be maintained as a site for ecotourism while simultaneously being used for intensive shrimp aquaculture. So, how can decision-makers reconcile conflicting interests and decide which use(s) is (are) most beneficial to society as a whole? Economics provides tools to answer this question.

Valuation concepts relate to human welfare, where human welfare is measured as each individual’s assessment of his or her well-being. The key is determining how changes in ecosystem goods or services affect an individual’s well-being and then estimating how much a person is willing to pay to maintain those services that have a positive impact, or how much a person is willing to accept as compensation for giving up those services (Barbier 2011).

Economics relies on the use of money as a "common measuring rod". The values to society of the provided goods and services are all quantified in money to make them comparable. These values are measured so as to reflect society’s preferences for the environmental goods and services provided. For goods and services that are not exchanged in the market, economists have developed methods to estimate their value to society as a whole. These economic values help quantify trade-offs between different goods and services: for instance between agricultural production and flood protection. Measuring these trade-offs helps identify the best land use from the point of view of society as a whole and provides one way to arbitrate conflicts.

Stated simply, an economic valuation is “the process of assigning a monetary value to ecosystem goods and services. It quantifies the benefits provided by ecosystems and the impact of ecosystem changes on the well-being of people.” GIZ (2012)

To summarize, there are several reasons why estimating the benefits of ecosystem services are useful (King and Mazzotta 2000):
• To consider the public’s values, and encourage public participation and support for environmental initiatives.
• To compare the benefits of different projects or programs.
• To prioritize conservation or restoration projects.
• To maximize the environmental benefits per dollar invested.
• To justify and decide how to allocate public spending on conservation, preservation, or restoration initiatives.

Why Value Mangroves?
The undervaluation of the natural products and ecological services provided by mangroves has been a major driving force behind their conversion and degradation (Rönnbäck 1999). This is because in the absence of information on the economic value of mangrove ecosystems to compare against the economic value of alternative public investments, the importance of mangroves is frequently overlooked (Brander et al. 2012). Additionally, unless the value of the ecosystem services provided by mangroves to coastal communities is estimated, it is difficult to convince policy-makers to consider land use policies which favor mangrove conservation and sustainable use. Finally, by valuing ecosystem services provided by mangroves, their destruction for economic development can no longer be viewed as “costless” (Barbier et al. 2012).

Valuation of ecosystem services is based on the concept of Total Economic Value
Total economic value (TEV) is one of the most common frameworks for environmental valuation (EMMA). This framework divides the total economic value of a good or a service into a use value and a non-use value. Use value refers to the benefit derived from the use of the environmental good or service. Use values can be direct or indirect.

Direct use values are derived from some sort of physical interaction with the environment, either consumptive or nonconsumptive. For example, direct uses of the mangrove include harvesting of fish, timber and other wild resources, recreation and tourism (Barbier 2012).

Indirect use values are those which stem from the support and protection of economic activities and livelihoods that have directly measurable values (Barbier 2012). An important indirect use value of mangroves is their role in serving as nursery and breeding habitat for some commercially valuable fish species which migrate offshore as adults. Other important indirect use values of mangroves include their ability to protect coasts from storms and prevent coastal erosion (Barbier 2012).

Non-use values are values allocated by society to goods and services but do not stem from the use of these goods and services. You might for instance value the Sundarbans mangrove forest even if you do not nor will ever use it. Non-use values can be further broken down into Option, Existence, Bequest and Stewardship values (See below).
Option value is the value allocated by society to the potential future use of a good or service and accounts in some measure for uncertainty. For instance, you might live far away from a mangrove but would still like to be able to enjoy bird watching in that mangrove at some point in the future. You would therefore be ready to pay to protect the mangrove and maintain the option to watch the birds later in your life.

Existence values refer to the value placed by society on the existence of an environmental good or service. For instance, you may never have the opportunity to personally see a mangrove forest, but you like the idea that it exists and would be happy to pay to help preserve its existence.

Bequest value is the value placed by society on the environmental state passed onto the next generation. For example, you might want your children to live in a region where it is possible for mangroves to exist and therefore place a value on bequeathing them such an environment.

Stewardship value is the value placed by society on the maintenance of a healthy environment for all living organisms and not just humans. Conservationists and people living off services provided by the environment (farmers, fishers...) typically have stewardship values.
Most valuation studies do not assess the full range of ecosystem services; rather they estimate the value of only a few services (TEEB 2010). Usually only the direct use goods and services provided by mangroves have been included in economic calculations (e.g. fishery resources) (MacIntosh and Ashton 2002). This is because markets exist for goods such as fish and timber and therefore their value can be more easily monetized. However, the direct use values of mangroves represent only a minor part of their total value (MacIntosh and Ashton 2002).

The indirect uses of mangroves include nutrient cycling, erosion control, water purification and support for offshore fisheries. Because no markets exist for such services, their value is not easily monetized and therefore these non-marketed benefits are not considered in coastal development decisions (Barbier 2007). While valuing non-marketed ecosystem services represents a unique challenge (Barbier 2007), this process is important for capturing the full value of mangroves. By accounting for both direct and indirect use values, decision-makers will be provided with the real cost of converting mangroves to seemingly more profitable endeavors.

**Major Valuation Methods**
Below we outline four of the major families of valuation methods and their associated sub-families (Russi et al. 2013). In reviewing these methods, it may be useful to keep in mind that the outcome of the valuation process will depend on what the stakeholders value, whose values count, who benefits and how social and ecological systems interlinkages are accounted for (Russi et al. 2013).

1) **Market-based valuation**: This approach uses market-prices to estimate the value of ecosystem services. Associated sub-families include:

- **Market price**: The ecosystem product or service, or its equivalent is sold in the market. Therefore the value is based on the price of goods in the market. For example, timber is bought and sold in the market; therefore their value is indicated by their price.

- **Cost-based approaches**: Value is based on the cost of replacing, mitigating or avoiding loss from damaged ecosystems. For example, estimating the coastal protection function of mangroves by calculating the cost of replacing them with man-made sea defenses

- **Production function approaches**: The value of an ecosystem service to another service is calculated. Based on how an ecosystem service influences the productivity of another service. For example, the nursery function of mangroves is often treated as an input to marine fisheries.

2) **Revealed preference**: Consumers ‘reveal’ their preferences through their behavior and purchases. Based on the observation of individual choices within an existing market. Associated sub-families include:

- **Hedonic pricing**: Based on the use of a surrogate market to estimate the value of non-marketed goods. Typically used for housing or property prices – e.g., estimates the implicit price paid for environmental characteristics of the area a property is in, through the differences in the property prices of different areas (UNEP-WCMC 2011).
Travel cost method – Used for determining recreational value. For example, estimating the value of a protected area through the amount of time and money people spend visiting it (Russi et al. 2013).

3) Stated preference: Includes methods that use surveys, questionnaires, interviews and/or ranking exercises to assess societal preferences. Associated sub-families include:
Contingent valuation – Involves asking people to state how much they are willing to pay to conserve a given non-marketed good or to accept a reduction in provision in order to estimate the economic value of this good
Choice modeling – Also called ‘choice experiment’ or ‘conjoint analysis’ and attempts to model a respondent’s decision making process.

4) Benefit transfer: Sometimes called, “value transfer”. Consists of “transferring” economic values from one case study to a similar location or context. This approach can be applied to market-based valuation, revealed preference and stated preference methods.

Selecting a methodology
So with all these methods available to us, how do we choose the best method to use? The methodology you choose will be determined by the parameters of the assessment context.
Scope: Includes the geographic extent of the study, the extent of consultation, amount of detail, resolution of the data, timeframe, number and level of detail of ecosystem services to be included in the assessment
Skills and capacity: The skills and capacity which each team member brings to the assessment will vary and may influence the type of methodology selected.
Data quality and availability: Multiple data sets of high quality will allow for a robust assessment; however lack of data will limit the scope, budget and ecosystem services included in the study.
Timeframe: In some cases, an assessment may be connected to the timeline of specific funding, a certain policy or management decision.
Ecosystem services: The number and type of ecosystem services to be included in the assessment must be considered. A comprehensive assessment of a single ecosystem service is likely more useful than a partial assessment of all services.
Budget: The budget is the total amount of funds available to conduct the assessment. This may partly determine the scope of the assessment, services to be assessed and methodology.
Cultural context: Cultural context will influence the indicators used in the assessment as well as the selection of ecosystems and their services. For example, countries for which fisheries form a large part of their economy may decide to focus on the contribution of mangroves to this resource.

The table below provides a general outline of the various valuation methods and types of values that they are commonly used to assess. In the next section we will explain in more detail how and why different valuation methods are used to assess certain services.
**Methods** | **Value Most Often Assessed**
--- | ---
**Market Valuation** | 
Market Price | Direct and indirect use  
Cost-based | Direct and indirect use  
Production function | Indirect use  
**Revealed Pricing** | 
Travel Cost | Direct use  
Hedonic Pricing | Direct and indirect use  
Contingency Valuation | Use and non-use values  
Choice Modelling | Use and non-use values  
**Stated Preferences** | 
Benefits transfer | Use and non-use values  
**Benefits transfer** | 
Benefits transfer | Use and non-use values  

Adapted from TEEB 2010

**Strengths and Limitations of Valuation Methods**

The methods we have described differ substantially in terms of their validity, reliability and applicability. Additionally, some methods are much more costly and time-consuming than others. Consequently, each valuation method has its strengths and limitations. It is the researcher’s responsibility to decide which method is best to apply to the respective study site based on the limitations, local circumstances and environmental setting.

<table>
<thead>
<tr>
<th>Valuation Method</th>
<th>Strengths</th>
<th>Issues and Limitations</th>
</tr>
</thead>
</table>
| Market Price | • Price, quantity and cost data are fairly easy to obtain and understandable for goods and services which have established markets.  
• Uses observed data of actual preferences | • Markets do not always reflect true economic value  
• Limited to those ecosystem services for which markets exist |
| Cost-based | • Can be easier to measure the cost of producing benefits rather than the benefits themselves  
• Depends on the existence of relevant markets for the ecosystem service in question, e.g., man-made defences being used as a proxy for mangrove storm protection | • Use costs as a measure of benefit, which is not always accurate  
• Methods do not consider social preferences for ecosystem services, or individuals’ behavior in the absence of those services  
• Can potentially overestimate actual value |
| Production function | • Can estimate the value of ecosystem services that are easily recognized by society  
• Relevant data is often readily available  
• Methodology is fairly straightforward | • Limited application to those resources which can be valued as inputs to production of marketed goods  
• Requires deep understanding of the relationship between changes in a biological resource or ecological function on an economic output |
| Travel Cost | • Can be accurately used to estimate the value of recreational areas and easily used | • Limited to recreational benefits only  
• Can be data intensive |
<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hedonic Pricing</td>
<td>• Can be used to estimate values based on actual choices</td>
<td>• Scope of environmental benefits that can be measured is limited to things related to housing prices.</td>
</tr>
<tr>
<td></td>
<td>• Data on property and sales readily available through many sources</td>
<td></td>
</tr>
<tr>
<td>Contingency Valuation</td>
<td>• Very flexible, able to capture both use and non-use values</td>
<td>• Several potential biases</td>
</tr>
<tr>
<td></td>
<td>• Only option able to capture both use and non-use values</td>
<td>• Estimates of non-use values are difficult to validate</td>
</tr>
<tr>
<td>Choice Modelling</td>
<td>• Allows respondents to think in terms of tradeoffs, which may be easier than directly expressing dollar values</td>
<td>• Data analysis is typically complex and requires advanced</td>
</tr>
<tr>
<td></td>
<td>• Respondents may find some tradeoffs difficult to evaluate because they are unfamiliar</td>
<td>• Potential bias in responses</td>
</tr>
<tr>
<td>Benefits transfer</td>
<td>• Typically less costly and time consuming than conducting an original valuation study.</td>
<td>• If contexts are not similar results can be inaccurate</td>
</tr>
<tr>
<td></td>
<td>• Can quickly provide crude estimations which may be sufficient for project goals.</td>
<td>• May be difficult to find appropriate studies</td>
</tr>
</tbody>
</table>

Sources: King and Mazzotta 2000; UNEP 2010

**Total Economic Value**

The range of TEV estimates for mangroves determined by different studies is highly variable (Spalding et al. 2010). This marked variance is likely due to discrepancies which result from using different approaches and methods as well as insufficient data. Additionally, climate change is an emerging issue which will influence the importance of certain ecosystem services – for example, the shoreline protection function of mangroves may increase due to rises in sea-level (UNEP 2011).

Global estimates for TEV of mangroves centre on a range of US$2,000 to US$9,000 per hectare per year (Spalding et al. 2010). This estimate is likely realistic in areas where mangroves are extensive, close to human populations and already being used, while it is less likely to be accurate for remote areas, low-diversity arid mangrove systems or for mangroves used mainly for subsistence in poorer countries (Spalding et al. 2010).

**Keep in mind...**

There is no single agreed upon total economic value for mangroves, or indeed any other ecosystem. This is because values will vary according to the following:

- The location – for example, whether or not mangroves are close to human populations, or more remote
- The length of time being considered and whether a prediction for the future is involved
- The beneficiaries of the service – some people will place higher value on services than others
- The method of valuation used and the assumptions made
4.6.1 Introduction to Payments for Ecosystem Services

The fact that mangrove forests are increasingly recognized as a valuable source of revenue should in theory make it easier to entice those who benefit from mangroves to make payments for the ecosystem services that they generate. Payments for Ecosystem Services (PES) are an economic instrument designed to provide incentives to land users for (agricultural) land and coastal or marine management practices that are expected to result in continued or improved ecosystem service provision, so a specific user or society will benefit more broadly. PES schemes can provide a new source of income to be used towards land management, restoration, conservation, and sustainable use activities and have the potential to provide a direct economic benefit and incentive to protect and sustainably use mangrove forests. So far, PES schemes have been developed around three main groups of services: water quality and quantity, carbon sequestration, and biodiversity conservation. Policy based decision support tools, such as the ‘Trade-Off Analysis’ and ‘Cost Benefit Analysis’, can help policy makers investigate the economic and institutional feasibility and benefit of using PES to protect mangroves, as an alternative to conventional environmental policy tools. Important aspects to consider for implementation are clearly defining and allocating local property rights to mangrove resources and determining the level of

One possible strategy to protect mangrove forests is through payments for ecosystem services (Albert et al. 2012) (PES). The ability of terrestrial forests to sequester carbon has led to the quantification,
purchase and trade of this ecosystem service through “carbon credits” (Albert et al. 2012). Because they store large amounts of carbon and are threatened by the financial appeal of conversion, mangrove ecosystems are an ideal target for carbon financing (Murray et al. 2010). Creating credit schemes for carbon sequestered in mangroves and other coastal ecosystems is an incentive-based method that can provide financial motivation to protect coastal and marine habitats.
4.7 Ecosystem-based Adaptation, Climate Change Vulnerability and Risk Reduction Strategies

Definitions:

- **Adaptation**: Making changes in order to reduce the vulnerability of a community, society or system to the negative effects of climate change. Includes building skills and knowledge as well as making practical changes such as strengthening coastal infrastructure, adjusting farming systems, and improving water management.

- **Mitigation**: Within a climate change context, mitigation is a human intervention to actively reduce the production of greenhouse gas emissions (reducing energy consumption in transport, construction, at home, at work etc.), or to remove the gases from the atmosphere (sequestration)

- **Vulnerability**: The degree to which a human or natural system is susceptible to, or unable to cope with, adverse effects of climate change. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.

Coastal Disaster Risks and the Need for Risk Reduction

The coast is a dynamic and complex environment and is affected by many sudden weather hazards including cyclones, tsunamis and tidal floods (Campbell et al. 2006). Coastal populations are thus exposed to many natural hazards (Adger et al. 2005). Exposure to coastal floods and tropical cyclones has increased dramatically due to increasing population density and location of assets along the coast (UNISDR 2011, Jongman et al. 2012). This exposure is expected to continue increasing due to climate change and its associated affects (IPCC 2007, Jongman et al. 2012).

Disasters occurring in the coastal zone are some of the most severe in terms of people affected, damages and fatalities. Of the most deadly worldwide events between 1980-2011, four out of the top ten affected coastal areas: the Haiti 2010 earthquake, the Southeast Asia Earthquake and Tsunami in 2004, Tropical Cyclone Nargis in Myanmar in 2008, the Bangladesh cyclone and storm surge of 1991 (Munich RE 2012). These same four events also were responsible for the largest number of disaster-related fatalities over the same period. In tropical coastal areas, storms are the deadliest events, followed by earthquakes and floods (EM-DAT, CRED).

Coastal disasters in the tropics are a major threat to coastal communities, particularly in developing countries where vulnerability is likely to be higher potentially due to the lower preparedness and lower response and recovery capacity (McGranahan et al. 2007). This situation leads us to question: *Why do people live in coastal environments which are more vulnerable to disasters?* Coastal areas are attractive
regions for economic growth and support an increasing proportion of the world’s population because they are inherently diverse and thus allow multiple social and economic niches (Adger 2000). Addressing disaster risk is particularly needed to ensure the security of people for whom the benefits of life on the coasts outweigh the risks.

**Ecosystem Based Disaster Risk Reduction**

Overall, ecosystem-based DRR encourages the sustainable management, conservation and restoration of ecosystems to reduce disaster risk, with the goal of achieving sustainable and resilient development (Renaud et al. 2013). This strategy is based on the premise that the multiple benefits which people derive from nature can be used for hazard mitigation (Renaud et al. 2013). Additionally, Eco-DRR generates multiple benefits for both people and ecosystems beyond those associated with DRR (PEDRR 2010).

In many cases, maintaining mangroves and other coastal habitats may be a better coastal defense strategy than adding artificial structures. Artificial structures can be expensive (Moberg and Rönnbäck 2003). For example, in Malaysia, the cost of replacing mangroves with hard engineering structures has been estimated at US$300,000 per km of coastline (ProAct Network 2008). Additionally, because mangroves respond to rising sea-levels by migrating inland (Alongi 2008), they may be significantly impacted where artificial structures present an obstacle to this migration (Gilman et al. 2008). Finally, the replacement of mangroves by artificial structures may lead to a loss of all the other goods and ecosystem services provided by mangroves. Therefore, coastal protection strategies which emphasize management of natural systems, such as mangroves, may not only be more cost-effective, but further benefit communities by providing co-benefits such as biodiversity conservation and livelihood enhancement by sustaining ecological production (Campbell et al. 2009, ProAct Network 2008).

**Ecosystems are important for disaster risk reduction for two major reasons:**

1) **Reducing physical exposure to natural hazards**

Healthy and well-managed ecosystems can lessen the impacts of some environmental hazards by providing a natural barrier or buffer to floods, landslides and storms (PEDRR 2010). In particular, the importance of coastal ecosystems in risk reduction is gaining increasing recognition. Coastal ecosystems, such as mangroves (Reviewed in Renaud et al. 2013)

- Reduce the height and speed of storm surges and tidal waves
- Absorb low-magnitude wave energy, reduce wave heights, erosion from storms and high tides
- Protect against hurricanes, storm surges and flooding
- Buffer against saltwater intrusion and adapt to slow sea-level rise

The term, “bioshield” refers to the use of vegetation for protection from extreme events (Feagin et al. 2009). In the context of disaster risk reduction, wetlands, mangroves and coral reefs have gained increasing attention for their potential role as buffers during extreme coastal events such as tsunamis and cyclones (UNEP-WCMC 2006, Granek and Ruttenberg 2007, Olwig et al. 2007). Mangroves, in
particular have been advocated for such a purpose (Feagin et al. 2009). The box below describes some of the pertinent issues related to the use of mangrove bioshields for protection against extreme coastal events such as tsunamis.

### Mangroves, bioshields and tsunamis

After the 2004 Asian tsunami, some evidence suggests that mangroves helped to reduce damage by dissipating the force of the tsunami and caught the debris washed up by it (e.g. UNEP 2005, IUCN, 2005). However, subsequent studies indicated that the protective benefit of mangrove was variable (Feagin et al. 2009). The general consensus is that mangroves play an important role in shore protection under normal sea conditions and during tropical storms and hurricanes (UNEP-WCMC 2006). However, during a tsunami, the buffering capacity of mangroves is more variable and often reduced due to the different nature of the waves and their much greater force (UNEP-WCMC 2006). In such scenarios, several factors will contribute to this variability, including: distance from the earthquake epicenter, presence of inlets and headlands, the gradient of the continental slope, shoreline elevation, the presence of dunes and other vegetation, and density of habitation and infrastructure (UNEP-WCMC 2006). The degree to which coastal ecosystems in general can attenuate extreme waves and thus provide protection is poorly understood (Barbier et al. 2008). Additional research is needed before we will be able to predict in what ways and where mangroves (and coral reefs) can help reduce the impact of a tsunami (UNEP-WCMC 2006).

It is important to recognize that ecosystems alone cannot reduce the impacts of extreme events (UNEP-WCMC 2006). Therefore, we must consider the use of bioshields, and mangroves in particular, as a complement to other disaster risk reduction strategies (Feagin et al. 2009). Substantial effort must still be devoted to lowering vulnerability to disasters through measures that increase capacity, lower exposure and sensitivity to hazards (Feagin et al. 2009). A priority is to reduce the human impacts (UNEP-WCMC 2006) which undermine not only the potential protective functions of mangroves, but also the wide variety of other services these ecosystems provide. Although they may be useful tools, mangrove bioshields should not be used to justify the absence of other disaster preparedness and risk reduction strategies such as early warning systems, construction of elevated shelters, planning initiatives, diversifying livelihood options and appropriate land use planning.

<table>
<thead>
<tr>
<th>Characteristics of mangroves reported to increase their effectiveness in coastal protection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Width</strong></td>
</tr>
<tr>
<td><strong>Density</strong></td>
</tr>
<tr>
<td><strong>Species</strong></td>
</tr>
<tr>
<td><strong>Forest structure</strong></td>
</tr>
<tr>
<td><strong>Height</strong></td>
</tr>
<tr>
<td><strong>Age</strong></td>
</tr>
<tr>
<td><strong>Stiffness of plant</strong></td>
</tr>
</tbody>
</table>
| **Orientation and geometry of the plantation** | This may relate to the location of the forest and the way the
Continuity and uniformity
The less fragmented the ecosystem is, the greater its attenuation capacity

Health
Relates to the resistance and resilience of ecosystems

Root system
Stabilizes the substrate where the trees are and roots also serve to dampen wave energy

Length
Is related to the area and width of the ecosystem and its role as a coastal defence

Source: Renaud et al. 2013

2) Reducing social-economic vulnerability to hazard impacts
In addition to their coastal protection functions, ecosystems are also important for sustaining human livelihoods. Mangroves, coral reefs and seagrass beds provide important resources to local communities by supporting fishing and tourism activities (Campbell et al. 2009). In locations where ecosystems and their services have been degraded, the ability of communities to adapt and recover from disaster is reduced. This is because after disaster events, affected communities often rely on their environment to meet vital needs such as water, food and shelter (PEDRR 2010). For example, in Southeast Asia, environmental degradation as a result of overfishing, coastal erosion, land-clearing and coral mining has reduced the potential for economic recovery from the 2004 tsunami due to the loss of traditional income sources related to coastal ecosystem services (Adger et al. 2005).

Assessing Vulnerability and Risk
The assessment of vulnerability focuses on gaining an understanding of how climate variability and change will impact coastal communities, the goods and services provided by natural resources, and human-built infrastructure. Vulnerability assessment for climate change in specific coastal regions considers four factors:

1. The nature and magnitude of climate variability and change;
2. The human, capital, and natural assets that will be exposed to and impacted by climate change and their sensitivity to climate change;
3. The health of coastal habitats and ecosystems; and
4. The current capacity of coastal communities and ecosystems to adapt to and cope with climate impact.
Detailed vulnerability and risk assessments for longterm anthropogenic impacts should be an integral part of coastal management strategies. Presently, the assessment of mangrove decline and of ongoing threats is piecemeal, with no clear understanding of large-scale patterns, trends in loss and degradation and a limited ability to forecast future change. Vulnerability and risk assessments consist of a combination of remote sensing, reconstruction of past sea level trends, site-based monitoring, community-based approaches and ecosystem valuations and are useful in the formulation of specific management options and adaptation strategies.

**Small Islands**

Small islands, whether located in the tropics or higher latitudes, have characteristics which make them especially vulnerable to the effects of climate change, sea-level rise, and extreme events. Countries. Relative to other coastal areas, low-lying islands, including many Small Island Developing States (SIDS) are more vulnerable to the impacts of climate change because they have relatively scarce natural resources (e.g., water resources, construction materials and physical space) and they have limited and high cost transportation options. Low-lying SIDS have little scope for adaptation and are particularly vulnerable to sea level rise and storm surge.

Less developed countries are vulnerable to climate change because of rapid population growth, much of it concentrated in coastal areas; high dependency on climate-sensitive industries such as fisheries, coastal agriculture and tourism; a degraded natural resource base; weak administration and governance systems; and poor transportation and communication infrastructure. Low lying coastal areas and deltas are highly vulnerable to sea level rise, extreme weather events and storm surge. Globally, at least 150 million people live within 1 meter of high tide level, and 250 million live within 5 meters of high tide.

**Mangroves in disaster risk planning and climate change adaptation**

Climate change will magnify disaster risks in two ways: 1) through the likely increase in weather and climate hazards, and 2) through increases in the vulnerability of communities to natural hazards,
especially through ecosystem degradation, reductions in food and water availability, and changes to livelihoods (ISDR 2008).

Conservation and restoration of mangroves and associated coastal ecosystems are important climate change adaptation strategies. Mangroves are not only valuable in climate change mitigation efforts but also play an important role in adapting to changing climates. In many settings, mangroves have the ability to attenuate waves, reduce storm surges and maintain their elevation in response to rising seas or land subsidence and can form a critical part of coastal defence planning. Wind and wave action can be rapidly attenuated as they pass through mangroves, while wide mangrove barriers can even have some effect against storm surges by slowing the flow of water and reducing inland flooding.

Over longer time frames, mangroves can also maintain or increase their elevation by capturing sediments and adding organic matter to soils which enables them to keep pace with rising sea levels. These important roles are variable and hence the inclusion of such functions in management and planning requires detailed site level assessment, but in many settings mangroves can be of immense value. There is also growing cognisance of the possibility of using mangroves alongside hard engineering as a form of hybrid engineering for coastal defence.

**Ecosystem-based adaptation (EbA) – Using natural solutions for resilience to climate change impacts**

Ecosystem-based adaptation (EbA) is the use of biodiversity and ecosystem services to help people adapt to the adverse effects of climate change. It includes the sustainable management, conservation and restoration of ecosystems. EbA is closely related to ecosystem-based disaster risk reduction (eco-DRR) because both approaches recognize the role of healthy, well-managed ecosystems in supporting communities to prepare for, prevent, cope with and recover from disaster situations and the impacts of climate change. Thus, EbA measures often complement disaster risk reduction objectives (Colls et al. 2009) and *vice versa*.

*What is EbA in practice?* We provide some examples below (UNFCCC 2011, Colls et al. 2009):

- Coastal defense through maintenance/restoration of coastal wetlands to reduce flooding and control erosion
- Conservation/restoration of forests to stabilize land slopes and regulate water flow
- Establishing and managing systems to ensure continued delivery of ecosystem services – e.g. through protected areas
- Managing ecosystems to complement, protect and extend the longevity of hard infrastructure
- Sustainable management of upland wetland, floodplains and forests for maintenance of water flow and quality
- Sustainable management of grasslands and rangelands, to enhance pastoral livelihoods and increase resilience to flooding and drought
EbA has multiple benefits (UNFCCC 2011, Colls et al. 2009), including reducing disaster risk:

- **Livelihood sustenance and food security**: Through protecting and restoring healthy ecosystems so that they are resilient to climate change impacts, EbA strategies can help to ensure continued access to essential natural resources so that communities can better cope with current climate variability and future climate change.

- **Sustainable water management**: Climate change and rising temperatures will lead to more water shortages for both agricultural and domestic purposes. Protecting, restoring and managing ecosystems lead to improved water quality, increased groundwater recharge and

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**Case Study: Mangrove Planting for Coastal Protection in Vietnam**

Vietnam is one of the most typhoon-impacted countries in Asia. Each year, an average of four typhoons and many more storms cause extensive destruction in this low-lying country. Since 1994, the Red Cross has planted and protected 12,000 hectares of mangroves in Vietnam. These mangroves protect 110 kilometres of the 3,000-kilometre sea dyke system that runs along Vietnam’s coastline. The financial savings from this project have been substantial; while the planting of mangroves has cost around US$1.1 million, it has reduced the cost of dyke maintenance by US$ 7.3 million per year. Importantly, the benefits of this project have not just been monetary; lives, property and possessions have been saved. For example, when Typhoon Wukong struck in October 2000, the dykes behind mangroves were not damaged and there were no fatalities inland of the protected dykes. This is a major contrast to the situation before mangroves were planted, when waves would breach the dykes and flood the homes of people inland. In addition to reducing the impacts of storms, the mangroves have improved the livelihoods of an estimated 7,750 families who benefit from selling, molluscs, shrimp and crabs that inhabit the mangrove.

Adapted from IFRC 2002
reduced surface water run-off during storms. Resilient ecosystems protect water quality and water supplies.

- **Disaster risk reduction**: Healthy ecosystems are important for protecting infrastructure and enhancing human security. By investing in protection and management of ecosystems we can maintain their natural buffering capacity against weather related hazards.

- **Biodiversity conservation**: EbA can safeguard and enhance protected areas and fragile ecosystems. Intact and interconnected ecosystems that can adjust to changing environmental conditions help maintain biodiversity.

- **Carbon sequestration**: Sustainable management of forests can ensure the continued sequestration of carbon by improving overall forest health. At the same time it protects the other ecosystem services these forests provide. Conservation and/or restoration of peatlands (e.g. mangroves and peat swamp forests) can protect carbon stores (this topic is discussed in detail in the “Mangroves and Climate Change” Unit). Mitigation can also occur through appropriate land and water management practices that sustain natural resources while minimizing further greenhouse gas emissions.

As part of an adaptation strategy, EbA approaches are useful because they (UNFCCC 2011):

- **May be more readily available to rural and poor communities**: EbA is the most relevant to poor communities who are often the most directly dependent on the services that ecosystems provide. EbA can be integrated into community-based projects for adaptation because it often
involves relatively low-cost approaches. For example, as natural buffers, ecosystems are sometimes cheaper to maintain than hard engineering solutions (Colls et al. 2009).

- **May be a better choice, economically:** In several instances, natural ecosystems can provide services at a lower price than hard engineering approaches (Russi et al. 2013). For example, restoring and maintaining wetlands is often cheaper when compared to man-made infrastructure solutions (Russi et al. 2013). In developed countries, improvements in water security have been achieved through expensive technologies (e.g. dams, pipes) which, although effective, may also degrade ecosystem services (Russi et al. 2013). However developing countries, which have high vulnerability to water insecurity, often cannot afford pricey technological solutions (Russi et al. 2013). In order to secure water availability and also reduce the impact of water-related disasters, a wise response by developing countries may be to utilize wetlands for water management (Russi et al. 2013).

- **Provide a range of co-benefits:** EbA approaches can provide many social, cultural and economic co-benefits (UNFCCC 2011). For example, mangrove conservation can provide protection against storm surges, sea-level rise and coastal inundation (adaptive function). However, it can also lead to employment options (e.g. fisheries cultivation-social function), generation of income for local communities (economic function), conservation of unique species (biodiversity function) and conservation of carbon stocks (mitigation function) (UNFCCC 2011).

EbA and Eco-DRR are very similar in terms of their outcomes and principles. They differ primarily through the time-scale involved (Powerpoint). Eco-DRR is mainly concerned with acute shocks, while EbA chiefly address chronic stresses (Powerpoint). Eco-DRR is more likely to include immediate interventions such as evacuation and early warning systems. However, it should now be evident that effective ecosystem management plays a central role in both disaster risk reduction and climate change adaptation (UNEP 2009). See the diagram below for an illustration of this.

![Diagram of Ecosystem Management, Climate Change Adaptation, and Disaster Risk Reduction](image-url)
The central role of ecosystems in climate change adaptation and disaster risk reduction
(Adapted from UNEP 2009)

The role of mangroves in climate change adaptation and disaster risk reduction should be integrated in local and national adaptation plans. National adaptation and disaster risk reduction plans and actions should:

- Encourage the conservation and restoration of mangroves as part of “natural coastal infrastructure”, recognizing their role in reducing vulnerability and increasing resilience to climate change impacts.
- Require the use of environmental impact assessment when planning and installing artificial coastal defences in or close to mangrove forests, considering the risks such structures may pose to the mangroves and to all associated ecosystem services.
- Consideration should also be given to using mangroves alongside built infrastructure as “hybrid engineering” where protection from mangroves alone may not suffice.

Marine Protected areas and EbA

As climate change intensifies, its damaging effects increase, and coastal communities are particularly at risk because there are specific impacts that degrade coral reefs and mangroves, reducing their coastal defense capabilities, at the same time that rising sea levels and more intense storms create greater damage to coastal communities. While MPAs cannot mitigate all climate change impacts affecting species and habitat, MPAs are seen as an essential part of the response to climate change because of their capacity to enhance resilience to change. They may also serve a mitigating role through the capacity of certain of their ecosystems (especially mangroves) to lock carbon up in long-term stores. More generally, effectively managed protected areas (terrestrial and marine) maintain intact ecosystems to buffer local climate, reduce impacts of extreme weather events, and provide other ecosystem services such as food and medicines, air quality regulation, water purification, aquifer recharge and erosion control. Designing and managing MPAs for resilience offers us a potentially effective means to help address the present climate and anthropogenic challenges, as well as the uncertainties of the future. The first step is to put in place management sufficiently effective to move them back from their currently degraded states, because they can only help buffer against climate change if they are in good ecological condition.

In the face of climate change MPAs can be used to:

- Maintain coastal buffering habitats like coral reefs and mangroves;
- Maintain fisheries productivity through maintaining healthy ecosystems
- Create refugia for sensitive and critical species and cortical sources of larval recruits
- Allow for a buffer zone and space for habitats to migrate to due to changes in temperature
5.0 Policies for Mangroves

5.1 Global Policies for Mangrove Protection

At the international level, a common approach to major environmental policy issues has been to formulate conventions, treaties and agreements. These represent collective agreements among the international community over a common global or regional issue and provide a means of regulating access and exploitation of commonly shared resources. Well-established conventions and treaties relevant to mangrove conservation offer an opportunity to strengthen management.

There are currently more than half a dozen regional and international agreements that are relevant to mangroves and afford them some level of protection, at least on paper (See the table below). A number of these have even been in force for over 50 years. There are a number of existing international frameworks available to help countries to conserve and manage mangrove biodiversity. These include:

1. International agreements for regulating pressures on marine resources;

2. Bioregional management approaches; and

3. Protected area frameworks, such as the Ramsar Convention and Man and the Biosphere (MAB) Programme.

The designation of sites under any of these international mechanisms offers considerable prestige and comes with some degree of support and collaboration; it also provides an international profile, which means that they receive closer scrutiny, which prompts wise management. Despite their existence, the current trend of global decline in mangroves indicates that these measures have not been very successful. Inadequate implementation of these treaties and instruments often means that legal protection is not established by the countries, while the treaties themselves have insufficient penalties for noncompliance. Governments need to come together to create synergies and streamline agreements so that their effectiveness is strengthened. For countries that have signed up to these agreements the main challenge is to put in place the measures required to give effect to these principles and commitments and achieve targets.

Traversing Political Boundaries

In the context of the coastal zone and mangrove forest ecosystems, one of the great advantages of these international protocols is that they can, in principle at least, be applied in trans-boundary situations. This is clearly important in many geographical settings worldwide where mangrove ecosystems traverse political boundaries. While international cooperation at the policy and planning stages is usually successful, conflicts between neighbouring countries or states are more common at the operational stage due to different development priorities and economic interests.
Coordinating Global Policies for biodiversity and climate change

The unique location of mangroves between the land and sea, their carbon management role, and the fact they are coastal wetland forests allows them to be considered under a range of global policy agendas; coordinated action must be ensured. Action on climate change has opened a way to broaden the portfolio of strategies aimed at protecting mangroves. The inclusion of mangroves and blue carbon in climate change agendas, such as the UNFCCC, would be a good first step towards coordinated action.

A second step could aim for climate change to be mainstreamed across the different international biodiversity, forest, wetland and coastal portfolios, to ensure coordination and incorporation of climate change into new policies. Some efforts are already underway. Biodiversity related conventions (such as the CBD and RAMSAR) have urged their member countries to integrate climate change issues and actions into national strategic biodiversity action plans (NBSAPs) and at the same time include mangrove ecosystems in their climate change national adaptation plans of action (NAPAs). Efforts to raise blue carbon awareness are mounting and a number of multilateral, bilateral and private sector initiatives exist which support blue carbon investments in coastal wetland projects.

Millennium Development Goals

Food security  Conservation and maintenance of mangrove ecosystems is essential for the achievement of the Millennium Development Goal to eradicate extreme poverty and hunger (MDG 1). Effective management of mangroves is an achievable and practical way to help ensure food security for many coastal communities. Healthy mangrove forests are critical for the maintenance and enhancement of food security; through the production of numerous fishery and forest products, by supporting commercial coastal and offshore fisheries, and by providing locations for aquaculture. Seafood provides 4–16% of the animal protein consumed worldwide. Aquaculture for fish and shrimp is now the fastest growing food producing industry in the world; the FAO (2000) estimates that by 2030, over half of the fish and shrimp consumed worldwide will be produced by aquaculture. There is ample evidence that removal of mangroves leads to a decline in coastal fisheries production and the loss of potential for development of integrated aquaculture and fisheries within and adjacent to mangroves themselves. Healthy mangrove ecosystems will become increasingly important for food security as the demand for (sea) food increases with global population growth.

Poverty alleviation There is a strong link between mangrove ecosystem degradation and the persistence of poverty in many rural coastal communities. The destruction and degradation of mangroves has strong socio-economic impacts. Improved appreciation of the range of values of mangroves may be useful in making appropriate decisions for more efficient and sustainable use. Community based poverty reduction programmes are needed where restoration and management of mangroves is implemented while providing communities with suitable alternatives to mangroves dependency (for domestic consumption and commerce). Successfully applied, these efforts can succeed in improving the ecological conditions of mangroves as well as the livelihoods of local communities.
Integrated management of biodiversity within poverty reduction strategies and food security planning is critical.

**Table. International and regional agreements that apply to mangroves**

<table>
<thead>
<tr>
<th>Agreement</th>
<th>Year Instated</th>
<th>Number of Parties†</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convention on Biological Diversity (CBD)</td>
<td>1993</td>
<td>193</td>
<td>CBD’s objectives include: conservation of diversity, sustainable use of components associated with biodiversity, and equitable distribution of benefits arising from the utilization of genetic resources. It relates to mangrove protection in some of its seven thematic programmes including: Forest Biodiversity and Marine and Coastal Biodiversity as well as through cross cutting themes such as Protected Areas, Sustainable Use, Biodiversity for Development and Climate Change and Biodiversity. Furthermore, nearly all the Aichi Targets, agreed to at the 10th Conference of the Parties of the CBD in Nagoya, Japan (2010) have some relevance to habitat protection, and directly or indirectly to the protection of mangrove ecosystems. For example targets 5, 7, 11 and 15 relate to the protection of forests.</td>
</tr>
<tr>
<td>Ramsar Convention on Wetlands (Ramsar)</td>
<td>1975</td>
<td>168 (2013)</td>
<td>Ramsar’s goal is to provide a framework for national action and international cooperation for the conservation and sustainable use of wetlands and the resources they provide. Ramsar members are committed to designating different sites according to a number of categories that assign ‘international importance’. This encourages parties to undertake more comprehensive reviews of their wetlands, thus facilitating their designation as protected sites. In 2009, there were 215 reported Ramsar sites (in 65 countries and territories), that included mangroves, and presently, over 15 million hectares of mangrove wetlands are under protection and sustainable use as part of the Ramsar Convention.</td>
</tr>
<tr>
<td>UNESCO Man and Biosphere Programme (MAB)</td>
<td>1977</td>
<td>105 (2008)</td>
<td>MAB involves the identification and preservation of biosphere reserve sites. It is not legally binding, but offers a unique cooperative approach. The sites are identified where a conservation function can be placed alongside development and science. MAB assists communities to effectively manage their resources through: establishing formal management systems, supporting scientific</td>
</tr>
</tbody>
</table>
assessments, providing international recognition, and facilitating information sharing with other biosphere reserves across the globe. In 2008, there were 34 MABs (in 21 countries) that included mangrove sites.

<p>| <strong>UNESCO World Heritage Convention (WHC)</strong> | 1975 | 189 | WHC is an international agreement that aims to protect places of exceptional universal value. The convention links nature conservation and cultural preservation; recognizing the fundamental need to preserve the balance between humans and nature. In 2008, there were 31 designated WHC sites (in 18 countries) that included mangroves. Most of these sites had mangroves as major or defining habitats that were central to their World Heritage status. |
| <strong>Convention on Migratory Species (CMS)</strong> | 1979 | 117 | CMS strives to conserve terrestrial, aquatic and avian migratory species and their habitats across the globe. This convention is relevant because mangrove forests provide habits and breeding grounds for many species of migratory birds. |
| <strong>Convention on the International Trade of Endangered Species (CITES)</strong> | 1975 | 175 | CITES aims to monitor and regulate the international trade of wild plants and animals in order to preserve and protect these populations. Invasive species have been involved in the destruction of mangrove habitats and as such CITES is a significant policy in the effort to preserve mangroves. |
| <strong>Agreement on the Conservation of African-Eurasian Migratory Waterbirds (AEWA)</strong> | 1999 | 65 | Originally established under CMS but now an independent international treaty that covers 255 species of birds ecologically dependent on wetlands for at least part of their annual cycle. Parties are called upon to engage in a wide range of conservation actions addressing key issues such as species and habitat conservation. |
| <strong>United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol</strong> | 2005 | 192 | UNFCCC (through its Kyoto Protocol) is an international agreement aimed at mitigating the effects of climate change. The main feature of the agreement is that it sets binding limits for 37 industrialized countries and the European community to reduce their GHG emissions. The Kyoto Protocol is relevant to mangrove forests because deforestation is a major contributor to GHG emissions and mangroves play an important role in the global carbon cycle and CO₂ sequestration from the atmosphere. Currently, proposals to reduce emissions from... |</p>
<table>
<thead>
<tr>
<th>Protocol</th>
<th></th>
<th>deforestation and forest degradation in developing countries that are being discussed under the UNFCCC (REDD+) could have significant implications for mangrove conservation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(UNEP) Regional Seas Programme (RSP)</td>
<td>1974</td>
<td>143</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RSP aims to mitigate the degradation of the world’s oceans and coastal environments (including mangrove ecosystems) through promoting sustainable management practices and encouraging countries with shared marine environments to collaborate. RSP operates through regional Action Plans, often enforced with a legal framework in the form of a regional Convention and associated Protocols. Today, more than 143 countries participate in 13 RSPs.</td>
</tr>
</tbody>
</table>

Source: Van Lavieren et al. 2012
5.2 Overview of Relevant Policies for Mangroves at the Regional and Local Level

There has been progress made in the development and/or review of various policy/legal instruments to enhance the management of coastal and marine resources in the countries of the region. While this progress has been made in various sectors through either sector specific or cross-sectoral instruments, only ICZM instruments are highlighted here. It is important also to acknowledge that for some countries, recent national constitutional reviews have captured environmental issues comprehensively e.g., the Kenyan Constitutional 2010, Article 69, section 1 provides that: The state shall “Ensure sustainable exploitation, utilization, management and conservation of the environment and natural resources, and ensure the equitable sharing of the accruing benefits; - including mangroves. Kenya has also formulated an Integrated Coastal Zone Management (ICZM) Policy and Action Plan with the goal of achieving integrated management of marine and coastal resources. This ICZM Policy and the Action Plan identifies various measures and strategies that need to be implemented to reverse environmental degradation and promote sustainable utilization of coastal and marine resources, including mangroves. Various sector legislation and policies have also been developed/reviewed by governments of the region and in some cases others are in progress. Only ICZM instruments are highlighted in the table below.

Status of ICZM policies/strategies in the WIO region

<table>
<thead>
<tr>
<th>COUNTRY</th>
<th>INSTRUMENT</th>
<th>STATUS</th>
<th>YEAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Tanzania</td>
<td>ICZM Strategy</td>
<td>Approved</td>
<td>2002</td>
</tr>
<tr>
<td>2. South Africa</td>
<td>Integrated Coastal Management Act</td>
<td>Approved</td>
<td>2008</td>
</tr>
<tr>
<td>3. Mauritius</td>
<td>ICZM Framework</td>
<td>Approved</td>
<td>2010</td>
</tr>
<tr>
<td>4. Kenya</td>
<td>ICZM Policy</td>
<td>Awaiting approval</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ICZM Action Plan</td>
<td>Approved</td>
<td>2011</td>
</tr>
<tr>
<td>5. Madagascar</td>
<td>ICZM Strategy/Action Plan</td>
<td>Approved</td>
<td>2010</td>
</tr>
<tr>
<td>7. Mozambique</td>
<td>ICZM Policy</td>
<td>Yet to start</td>
<td></td>
</tr>
<tr>
<td>8. Comoros</td>
<td>ICZM Policy</td>
<td>Approved</td>
<td>2010</td>
</tr>
</tbody>
</table>

The region-wide attempt to develop and adopt an ICZM approach in managing coastal and marine resources is highly commendable as it provided a platform for governance/management actions to be undertaken using an integrated approach, hence mitigating the hitherto applied sectoral approaches which have not worked effectively. For instance, in the past coastal and marine resources have been managed not only singly, but almost without consideration of inland activities and yet land-use practices upstream have significant impacts on ecosystems downstream. The current drive by the Nairobi Convention to develop a regional ICZM Protocol is in part a response to encourage a harmonized approach in implementation of ICZM actions in WIO countries.
5.3 Challenges for Sustainable Management and Need for Policy Reforms in the WIO

Like in most areas of the world, mangrove ecosystem in the WIO region face multiple management challenges. Throughout the WIO region mangrove wood products are heavily harvested for building materials and firewood. Mangrove areas have been converted for other land uses, including; shrimp aquaculture in Madagascar and plantation agriculture along River Rufiji in Tanzania and the Zambezi river in Mozambique. In Peri-urban areas, such as Maputo, Mombasa and Dar-es Salaam pollution from both oil spills and municipal wastes have led to losses and degradation of mangroves. Losses of mangroves have impacted local and national economies as indicated by shortages of firewood, decline in fisheries and increased shoreline erosion. Some of the root causes of losses and degradation of mangrove ecosystem in the region have been identified as; weak governance, population pressure, poverty and economic development in the coastal areas, and in adequate knowledge and awareness.

WIO countries have taken the initiative to conserve mangrove resources in the region. The first step was the linking of all the countries in WIO region in 1985 with one environmental convention - the Nairobi Convention. This convention entails Protection, Management and Development of Marine and Coastal Environment in the Eastern Africa Region. The second step was taken in 2009 with the adoption by member countries to Nairobi Convention of a Strategic Action Plan (SAP) for Land-based Sources and Activities Affecting the Marine and Coastal Environment in the Eastern African Region.

Specific to mangroves, the WIO countries have established, within the Nairobi Convention, a regional Mangrove Network (WMN). The network provides a forum for scientists, managers and policy makers from government and NGO institutions to contribute to solutions for addressing mangrove management challenges at national and regional levels. Complementing the current training course, WIO Mangrove Network has already implemented a number of activities that serve its primary objective, namely building capacity and raising the profile of mangroves as a critically important ecosystem that supports many livelihoods in the region and as valuable carbon sinks. The network is currently developing a synthesis book on status and conditions of mangrove resources in the WIO region.

At national levels, countries in the region are at different stages in the development and implementation of national mangrove management plans. Mainland Tanzania was the first country in the region (and indeed Africa) to develop a national mangrove management plan. The 1991 Plan divided mangroves of mainland Tanzania into ten management blocks. Unfortunately, the Plan was not fully implemented and has never been reviewed for its effectiveness. In 2010, Kenya initiated steps to develop a national mangrove management plan. The goal of the Plan is to enhance the integrity of mangrove ecosystem in Kenya and its contribution to the economy of the country through sustainable management and rational utilization. Other countries are yet to initiate steps to develop mangrove plans in their areas.
6.0 Field Sessions

The mangroves of Gazi Bay

One field site for the training course will involve Gazi Bay. This bay, in the Kwale district of Kenya is located 55 km south of Mombasa. The bay has a surface area of 18km$^2$ and is sheltered from strong sea waves by the presence of Chale Peninsula to the east, and a fringing coral reef to the south. On the landward side, Gazi Bay is bordered by 6.2km$^2$ of mangrove forests. The community in Gazi has done much to protect and restore the mangrove forests, as they depend on them for their livelihood (especially wood for building resources and fuel) and survival. As a result, they now have a robust ecotourism industry that centers on the mangroves.

A map of Gazi Bay
6.1 Demonstration and Use of Sampling Equipment

Survey of mangrove forest is a very important tool for sustainable utilization and management of mangroves. This is because it provides quantitative information on forest condition, particularly concerning composition, stand density, pole quality, and regeneration potential. Standard sampling procedures and techniques have been developed that enable effective mangrove forest resource assessment. These include selection of representative sites using sampling methods such as establishment of plots and/or line transects. In general, depending on the objective of the survey, transects may or may not be necessary; where necessary, they are set perpendicularly to the water line; with at least 50 m distance between any two adjacent transects and plots are established along them at an interval of ≥ 20 m. If the objective of the exercise is to provide a rapid forest assessment, transects may not be established. In this case, if available, aerial photographs or maps of the area are used to predetermine representative sites where plots will be randomly established. Circular, rectangular and square plots (or quadrats) are the commonly used for plot methods; while for plotless methods, point centred quarter method (PCQM) is commonly used. Standard plots of 10 m x 10 m each are widely used for mangroves. During the course of the training, common tools and methods used in studying mangroves will be demonstrated (See the table below):

Table: Survey tools and equipment

<table>
<thead>
<tr>
<th>Tool</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Compass and/or GPS</td>
<td>For measuring bearings/or marking plots</td>
</tr>
<tr>
<td>2. Forester’s caliper or diameter tape</td>
<td>Measuring stem diameter (dead and old)</td>
</tr>
<tr>
<td>3. Tape measure/ fiberglass tapes (≥ 30 m long)</td>
<td>For measuring distances</td>
</tr>
<tr>
<td>4. Clinometers (% scale)</td>
<td>For measuring tree height and slope</td>
</tr>
<tr>
<td>5. Dbh tapes</td>
<td>For measuring tree diameter at breast height</td>
</tr>
<tr>
<td>6. Graduated pole (≥ 5 m)</td>
<td>Normally use to measure height of trees (in place of professional clinometers)</td>
</tr>
<tr>
<td>7. Ropes and pegs</td>
<td>For marking plot boundaries. The ropes are also used in marking transects for measuring deadwood</td>
</tr>
<tr>
<td>8. Data sheets</td>
<td>Recording data</td>
</tr>
<tr>
<td>9. Handsaw and machete</td>
<td>For collecting deadwood samples and cutting destructive samples</td>
</tr>
<tr>
<td>10. Spring scales (1 kg and 300g)</td>
<td>For weighing destructive samples</td>
</tr>
<tr>
<td>11. Large plastic sheets</td>
<td>For mixing forest floor/destructive sample</td>
</tr>
<tr>
<td>12. Sample papers</td>
<td>For collecting wood and non-wood samples</td>
</tr>
</tbody>
</table>
6.2 Vegetation Characteristics of Mangroves

Mangrove phenology

Phenological studies are involved with the observation and documentation of the timings of life history events of plants. Such events include periods of maximal leaf appearance, leaf fall, flowering and fruiting and their relationship to seasonal changes (Duke 1990). Phenological patterns follow certain trends and cycles and are determined by a number of factors among them, geographical locations (latitudes) which dictate the climate and genetic variability including species type (Duke 2001). It is thus difficult to generalise phenological traits among and within species. Phenological studies are important as detailed year to year information on these traits helps in the understanding of the adaptations, dispersal, survival and distribution of plant species. Comparative information for individual species at widely separated points of their distribution is scarce (Duke et al. 1984). Mangrove phenology can be used as an indicator of mangrove productivity in terms of leaf gain and fall and also through its reproductive capacity in terms of flowering and fruiting.

Links between floral and leafing phenologies

Relationship between leafing and floral phenologies has been widely reported for various mangrove species, where vegetative activity (leafing rates) increases prior to flower and fruit production and declines when production of flowers and fruits is at maximum (Wium-Andersen and Christensen 1978, Duke 1990, Coupland et al. 2005). This has been attributed to resource partitioning within plants Duke et al. (1984). Other studies have indicated that there is considerable annual variation in the quantity of both flowers and propagules produced and that year to year variation was minimal in the timing of events at any single site (Wium-Andersen and Christensen 1978, Duke et al. 1984, Steinke and Charles 1984, Woodroffe et al. 1988). Continuous growth in *A. marina* has also been reported with maximum vegetative growth prior to flowering (Hegazy 1998, Wium-Andersen 1981). Mehlig (2006) reported continuous growth for *Rhizophora mangle* L. with leafing and fruiting occurring throughout the year and propagule production differences in areas with low and high salinities. Duke et al. (1984) observed that flowering and fruiting status of North-eastern Australian mangroves displayed a range of peak activity months, however there were some common trends for the mangrove species studied.
Documentation of mangrove phenology and its role in forest management.

Detailed site-specific phenological studies have thus been documented for the genus *Avicennia* (Wium-Andersen and Christensen 1978, Lopez-Portillo and Eczurra 1985, Duke 1990), *Rhizophora* (Gill and Tomlinson 1971, Wium-Andersen 1981) and *Ceriops* (Slim et al. 1996). However these studies are few to enable tangible comparisons with species occurring in various latitudes. *Avicennia* is the most widely distributed species across latitudes hence detailed studies on the phenology of the species is critical in extrapolating differences observed in the phenology of the species. Phenological studies of *A. marina*, *R. mucronata* and *S. alba* in Kenya through direct shoot observation has been documented (Ochieng and Erftemeijer 2002, Wang’ondu et al. 2010, 2013).
6.3 Mangrove Propagation Techniques

Mangrove forests are important for the enormous range of goods and services they provide to coastal human populations (FAO 1994). Increased demand of mangrove products has led to their overexploitation. Concerted efforts have to be made to reforest degraded mangrove areas in order to achieve the objectives of sustainable forest management. Quantitative findings have shown that reforestation has the potential of returning the lost forests and thereby sustain supply of mangrove goods and services (Kairo et al. 2008).

Studies have shown that natural mangrove forests are better seed producers than younger stands and should be preserved as seed stands (Clough et al. 2000, Nga et al. 2005). Continued loss of natural forests translates to scarcity of propagules for natural recruitment and rehabilitation programmes. In addition, both natural and reforested stands experience high rates of floral and propagule abortion rates (Coupland et al. 2006). Other factors limiting availability of propagules is that mature seeds of *A. marina* are highly recalcitrant (cannot withstand desiccation) (Farrant et al. 1993), coupled to the volatile environment of this species in terms of salinity and herbivory. Consequently, herbivory on propagules before dispersal on the parental plant can play a role in limiting supply of propagules and recruitment of seedlings (Louda and Potvin 1995). *Avicennia marina* has also been reported to exhibit the highest mean levels of propagule predation, followed by *R. mucronata*, (Farnsworth and Ellison, 1997). *Rhizophora spp.* also has a very prolonged fruiting process and propagule predation while still on the host plant and most propagules are aborted during fruit maturation (Coupland et al. 2006). These factors hamper the availability of mangrove seeds and can thus be a drawback to regeneration and rehabilitation efforts of certain mangrove species. Reproductive phenology of mangroves species also varies and may not coincide with planned restoration programmes. Vegetative propagation of mangroves would thus increase availability of saplings for planting throughout the year and ensure successful programmes.

Mangroves are mainly regenerated through propagules and seeds which can be planted directly in the field or first raised in a nursery and later transplanted to the field. However, pre and post dispersal propagule predation is a major hindrance of natural regeneration and raring seeds in a nursery enhance the survival of saplings in the field.

There are several methods that are used for mangrove propagation. These include:

- Direct planting of propagules from the wild
- Raising propagules in nursery and later having them transplanted.
- Planting of small seedlings collected from the wild after nursery raising
- Propagule cuttings
- Stem cuttings
- Air-layering
Direct planting of propagules has several drawbacks such as, propagule desiccation, dislodgement by wave and tides, predation and damage by debris (Saenger 2002). This makes this method unsuitable for sites with high wave energy. Propagules should thus be selected for protected sites or areas with mangrove stands.

Rearing of mangroves seeds in a nursery
Collection of propagules and nursery propagation

*Avicennia marina*

**Propagules are collected during the fruiting season.** Seeds for *A. marina* are collected from trees and floor of the forest. After collection the *A. marina* fruits are immediately transported to the lab, where unhealthy propagules and those damaged by insects were sorted out and discarded. Size of each propagule (diameter) is measured and grouped into four size classes (1.5-2.0 cm; 2.1-2.5 cm; 2.6-3.0 cm; and 3.1-3.5 cm). Mostly fruits in the size class 3.1-3.5 cm which are considered mature are few whereas those for the other classes are usually are plenty. The fruits are then placed in large basins and data recordings on buoyancy behaviour (floating or sinking,) with or without pericarp and loss of pericarp is recorded immediately after placement and at 1, 15, 26, 49, 59 and 74 hours. Those that sink after loss of pericarp were immediately planted in an already prepared seed bed in the *A. marina* forest. After planting percentage germination is growth is monitored until the saplings are ready for transplanting.

*Rhizophora mucronata*

*Rhizophora mucronata* propagules are harvested from trees, preferably those within the 31-40 cm, 41-50 cm and 51-60 cm size classes. However, very few propagules attain the size of 51-60 cm class as most drop from the mother plant at length of 40 cm or earlier. After sorting, the propagules are placed in gunny bags, covered and stored in a shady place in the forest to avoid desiccation and enhance rooting. After development of roots the propagules were planted in plastic bags filled with mangrove forest soil preferably from a *R. mucronata* stand. They are then arranged in a nursery in the *R. mucronata* forest. Data on percentage germination (appearance of first pair of leaves) and growth performance (shoot length and leaf number) are monitored and saplings should be ready for transplanting within 8 months.
The advantage of this method is that it provides year round supply of planting material which is important for large scale rehabilitation projects. Nursery raised seedlings are also highly successful in terms of survival and growth rates; height increase and number of leaves than propagules (Saenger and Siddiqi 1993, Toledo et al. 2001).

**Vegetative propagation techniques in mangroves**

**Mangrove propagation through propagule cuttings**

In the early 1980s, Thai foresters used this method for propagation of *Rhizophora apiculata* (Saenger 2002). Viviparous propagules are cut into three segments (top, middle and bottom). The segments are then treated with auxins (rooting hormones) and planted separately. Using segments >3cm results in 35-90% root formation (Ohnishi and Komiyama 1998). This method provides for 1.5-2 fold increase in available planting material for *Kandelia candel* and other species with longer propagules such as *R. mucronata*.

Propagules can also be cut into 4-5 cm pieces (de silva and Amarasinghe 2010). Phenolic compounds present in cuttings are removed using 10% and 5% phenol removing solutions. A volume of 100 ml phenol-removing stock solution (20%) is prepared by dissolving 20g of sodium carbonate and 20g of sodium tungstate and it is used to prepare 10% and 5% phenol removing working solutions (PRWS). A volume of 50ml of from the stock solution (20%) is mixed with 50 ml of distilled water to prepare 10% PRWS. 25 ml of stock solution is mixed with 75 ml of distilled water to prepare the 5% PRWS (Selvam et al. 2005).

The basal portion of the cuttings is immersed in 10% PRWS for 5-10 minutes. After the phenol removing treatments, propagule cuttings are washed 2-3 times with distilled water.
Indole Butric Acid (IBA) and Naphthalene Acetic Acid (NAA) hormone stock solutions are prepared separately by adding 1 g of each hormone into 100 ml volumetric flasks and then 1N NaOH is added drop-wise until the solids dissolved completely. Distilled water is then added to bringing the volume to 100 ml.

Treated seedling cuttings are then planted in polythene bags containing mangrove soil. White paint is applied on the exposed portion of the cuttings to reduce fungal attacks. Planted cuttings are placed in a shady place in the mangrove forest. Cuttings are continuously monitored and fresh water was supplied when necessary. Growth is monitored until the saplings are ready for transplanting.

**Rooting of stem cuttings:**

Semi-soft wood cuttings (about 30 cm in length; basal diameter 8–15 mm) are collected from secondary mangrove branches. Basal ends are dipped for 5 minutes in a rooting hormone solution to a depth of 1 cm. The terminal end is sealed with cow dung to prevent desiccation. Cuttings are then planted in polythene bags in sand: clay (1:1 w/w) substrate and placed in low cost mist chamber (60–90% relative humidity at 28-30°C, controlled through intermittent spraying with water) for 1 month. Cuttings are then transferred to a field nursery in mangrove forests (de silva and Amarasinghe 2010).

Various authors have also reported rooting of stem cuttings of many species through stem cuttings treated with IAA, IBA and NAA rooting hormones (Das et al. 1997, Basak et al. 1995).

**Mangrove propagation through air layering**

**Air-layering**

It is a method of inducing development of roots on branches while they are still attached to the trees. Roots are produced in small branches by applying root producing hormones and rooting media. Outer bark of the selected branch is removed 2-5 cm below the node using a fine blade. A bridge of the bark is made to a 2-4 mm thickness in a way to connect upper end of the mother plant and lower end of the daughter plant. Hormones, IBA and NAA are applied twice all around the wounded portion using a fine brush. A rooting medium is prepared by adding 5:2 ratios of coir dust and sand and brackish water added and mixed well. It is then applied around the wounded portion and wrapped using a transparent polythene sheet. Transplanting can be done after 14-16 weeks. This method has been suggested for *Sonneratia apetala* and *Xylocarpus granatum*. (Eganathan et al. 2000)
6.4 Mangrove Ecotourism

Mangrove forests provide a range of non-consumptive services to human. This includes different forms of tourism and recreation, and use for spiritual or religious value. These are classified as ‘cultural services’ or ‘landscape beauty’ (MEA 2005).

In the Gazi Bay, local women have established a mangrove boardwalk to make use of and benefit from the ‘landscape beauty’ provided by the mangrove ecosystem. The 500 m long boardwalk meanders through animal-rich mangrove forest and has resting points, signets at strategic points, and viewing platforms. Ranges of activities are included in the mangrove ecotourism package, including; mangrove planting, canoe trips inside the mangroves, excursions to the coral reef, bird watching and a guided tour to a traditional African village. These activities support local livelihoods and generate income to the management of the boardwalk. The extra revenue from the ecotourism is channeled to the community kitty in order to support prioritized sanitation and education programs in the village. This way it has been easier to communicate the concept of biodiversity and ecosystem services; and how they could be enhanced through a Payments for Ecosystem Service. Participants will have the opportunity to visit Gazi women boardwalk during the training.
6.5 Protocol for Assessment of Mangrove Forest Structure

1. With aid of a compass set plots of 10 m x 10 m in the selected sites. Put markers at the corners of the plot. The plots at the edges of the forest should be set at least 20 m from the forest edge.
2. Take GPS readings of each plot
3. Estimate vegetation cover (%); i.e. proportion of the ground covered by tree canopy
4. Within each plot, take measurements of all trees with stem diameter of ≥ 5 cm.
5. Using forest caliper measure stem diameter (DBH – diameter at breast height; usually measured at ~ 1.30 m above the ground). For Rhizophora trees take measurement at ~ 30 cm above the highest prop root.
6. Estimate tree height (m) using a hypometer or a graduated pole.
7. Note the number of stumps, recent as well as old cuttings, in each plot

Note the general observations regarding soil condition, macrofauna abundance and composition as well as other observable attributes within and around the plot.

**NB:**

a) Not all trees have uniform cross-section at point of DBH measurement, hence, in case of swell or deformity at 130 cm point, measure the diameter at a uniform section above or below 130, whichever is nearer.

b) Some trees are multi-stemmed below 130 cm, take measurement below the branching point if there is a uniform cross-section at ≥ 1.0 m above the ground. If not, measure DBH of each stem separately, but record in the NO. column as a, b, c, etc. for that tree (e.g. as 1a, 1b and 1c if tree NO. 1 has 3 stems branching below 130 cm).
6.6 Soil Sampling Protocol

Half-arc soil corer of known diameter is used in sampling mangrove soils. The sampler can take a cylindrical, ca. 1 m deep sediment core, when correctly operated. Four subsamples of the complete core are taken so that they represent sediment depth layers: 0-15 cm, 15-30 cm, 30-50 cm, and 50-100 cm, respectively. 5 cm long subsamples taken from the centres of the listed depth layers is taken for the analysis of bulk density and carbon concentration (see figure below). The cutting should be straight so that a perfect cylinder is formed from the subsample. Any error in the shape results in error in the bulk density of the subsample and consequently, the carbon stock estimate.

A good, undisturbed location is selected for coring. The sediment surface has to be untouched. It is also important that tree roots etc. obstacles will not prevent turning the handle when the sampler is driven into the sediment as follows:

1. The sampler is positioned on the selected spot and held as vertically as possible when pushed into the sediment. When the sampler is down in the sediment, turn around the sampler by the handle until the sampler begins to turn easily.

2. When the sample has been loosened by turning around the sampler, draw the sampler up carefully, in vertical position, avoiding any contact with the core. Do not turn the sampler any more while lifting it. That may contaminate the sample profile with materials from upper layers.

3. Lay the corer on a horizontal position and inspect the core. If the sample is not complete, or is disturbed, it should be discarded. At least an 80 cm long undisturbed core is needed. If new coring has to be made, the sampler is washed clean in order to avoid contamination by materials from the earlier sample. A complete, undisturbed core is always the best for further sectioning.

Mangrove sediment core taken using a half-arc soil sampler
6.6.1 Soil Analysis

- Samples are oven-dried at 60°C to constant mass in pre-weighed crucible.
- They are weighed and the **bulk density** is obtained using the following formula:

\[
\text{Soil bulk density (g m}^{-3}\text{)} = \frac{\text{Oven – dry sample mass (g)}}{\text{Sample volume (m}^3\text{)}}
\]

Where,

\[
\text{volume} = \text{cross – sectional area of the corer \times the height of the sample sub – section}
\]

- For maximum efficiency, the same sample analyzed for bulk density are used to analyze for the organic matter and organic carbon.

- Loss on ignition (LOI) determination of soil organic matter - oven-dried samples of known weight are placed in pre-weighed crucibles and set in a muffle-furnace for combustion at 450°C for 8 hours. The sample is then cooled in a desiccator and weighed.

- Organic matter content is determined as:

\[
\frac{\text{Initial weight (g)} - \text{Final weight (g)}}{\text{Initial weight (g)}} \times 100
\]

- **Soil organic carbon concentration** (%OC) may be gravimetrically determined from sample weight loss and a conversion factor, usually 1.724 based on the assumption that organic matter contains 58% organic matter.

- To directly determine the soil organic carbon concentration, colorimetric quantitation or dry combustion may be used.

- The total soil carbon pools are determined by summing the mass of each sampled soil depth. The soil carbon mass per sampled depth interval is calculated as:

\[
\text{SOC(Mg ha}^{-1}\text{)} = \text{bulk density(g cm}^{-3}\text{)} \times \text{soil depth interval (cm)} \times \%OC
\]

Where %C is expressed as a whole number.

- The total soil carbon pool is equal to the sum of the carbon mass of the soil depths.
6.7 Analysis of Vegetation Data

To adequately describe vegetation in a site after collecting the raw data, the following parameters must be calculated:

**Basal Area (g)**= the proportion on the ground occupied by the vertical projection of the tree trunk to the ground and its calculated as $g = \pi r^2$

**Stand density** = Number of individuals in a unit area and its calculated as
Density per hectare = (No. of stems in plots x 10,000)/Area of the plot

**Relative density** = (Number of individuals of a species/total number of individuals) x 100

**Relative dominance** = (Total basal area of a species/Basal area of all species) x 100

**Relative frequency** = Frequency of a species/sum frequency of all species) x 100

**Importance value (IV)**= product of relative measures of species density, frequency and dominance which are calculated as (Rel.density + Rel. dominance + Rel. frequency)

Importance value gives the overall estimate of the influence or importance of a plant species in the community.

**The complexity indices** ($I_c$) of each forest zone is computed as the product of number of species, basal area (BA) ($m^2 \text{ ha}^{-1}$), maximum tree height (m) and tree density (stems ha$^{-1}$) $\times 10^{-5}$

$I_c = \text{Number of species} \times \text{Basal Area (m}^2 \text{ ha}^{-1}) \times \text{mean tree height (m)} \times \text{density (ha}^{-1}) \times 10^{-5}$

In addition to structural parameters, many projects now are interested in understanding stand biomass and hence vegetation carbon. Stand biomass can be converted to volume using Biomass Conversion/Expansion Factors (BC/EF). This is the ratio between above-ground biomass in tonnes and growing stock in m$^3$.

**Where local biomass equation do not exist, aboveground biomass (AGB)** of each mangrove tree in a stand can be calculated using generalized biomass equations for mangroves (Komiyama, et al. 2005).

$$AGB = 0.251 \rho D^{2.46}$$

*Where*

- $AGB$= Tree AG biomass (kg)
- $\rho$= wood density (g/cm$^3$)
- $D$= tree diameter at breast height (cm)

Wood density exists for most mangrove species.
Annex 1 Course Organizers and Affiliates

**WIO Mangrove network** provides a forum for scientists, managers and policy makers from government and NGO institutions to contribute to solutions for addressing mangrove management challenges at national and regional levels. The network among others, focuses on expertise sharing and capacity development in mangrove research and management across the region; and raising the profile of mangroves as a critically important ecosystem that supports many livelihoods in the region and as valuable carbon sinks. Additionally, the network works to inform and promote the science and conservation of mangroves in this region. The Network is a lead partner on mangroves in the E. African region and complements the activities of both WIOMSA and the UNEP Nairobi Convention.

**Kenya Marine and Fisheries Research Institute (KMFRI)** ([www.kmfri.co.ke](http://www.kmfri.co.ke)) is a state Corporation in the Ministry of Fisheries Development of the Government of Kenya. They conduct aquatic research in Kenyan waters and related riparian areas, including their EEZ in the Indian Ocean. Part of their focus is on capacity building for mangrove assessment, restoration, and valuation in East Africa.

**Coastal Oceans Research and Development in the Indian Ocean (CORDIO), East Africa** ([www.cordioea.net](http://www.cordioea.net)) is a regional research-based not-for-profit organization, registered in Kenya, focused on marine and coastal ecosystems in the Western Indian Ocean. Their mission is to generate and share scientifically sound knowledge for developing solutions to the problems and challenges facing coastal and marine environments and people. CORDIO’s research and conservation work addresses problems that are linked in the WIO: growing population and consumption; limited resources and habitat; high dependency; low education and wealth; poor governance. CORDIO emphasis linked solutions to these problems: ecological and social resilience; adaptive capacity; environmental conservation; sustainable use; education, policy and governance; investment in livelihoods and improved capacity. CORDIO implements work across three sectors to search for solutions and to enable their implementation: Research and Knowledge; Management and Policy; Capacity Building.

**United Nations University Institute for Water, Environment and Health (UNU-INWEH)** ([www.inweh.unu.edu](http://www.inweh.unu.edu)) is a specialized capacity development UN institution for water-related programs in the developing world. It focuses on improvement of scientific understanding to foster sound decision-making. This is achieved through diffusion of scientific research and promotion of human and institutional capacity. UNU INWEH has coordinated an annual training course on mangrove ecosystems in South East Asia since 2004. Enhancing local capacity through an effective combination of North-South and South-South networks is integral to many of their projects.
The University of Nairobi: The University of Nairobi was established in 1956, and was then known as the Royal Technical College which admitted its first lot of A-level graduates for technical courses in April the same year. The Royal Technical College was transformed into the second University College in East Africa on 25th June, 1961 under the name Royal College Nairobi and was admitted into special relations with the University of London. The University’s vision is to be a world-class university committed to scholarly excellence and a mission to provide quality university education and training and to embody the aspirations of the Kenyan people and the global community through creation, preservation, integration, transmission and utilization of knowledge. The University of Nairobi is renowned for its enormous collaborations with local and international learning and research institutions in order to achieve its vision. The university will provide its research facility at the Moana field station located in Diani (Kenya South Coast) in addition to one of the lecturer and researcher (Dr. Wang’ondu) being a co-trainer.

UNEP Nairobi Convention (http://www.unep.org/nairobinconvention/) provides a mechanism for regional cooperation, coordination and collaborative actions in the Eastern and Southern African region. The Convention offers a regional legal framework and coordinates the efforts of the member states to plan and develop programmes that strengthen their capacity to protect, manage and develop their coastal and marine environment sustainably. This training course could contribute to the capacity building program under the Nairobi Convention. It is anticipated that the Nairobi Convention will support some of the costs for WIO participants to attend the training course.

World Wide Fund for Nature (WWF) “Coastal East Africa Initiative” (CEA-NI)

Mangroves for the Future (MFF) WIO initiative is supportive of this training course, which would fit under two of the MFF objectives; 1) improve, share and apply knowledge to enhance resilience and reduce vulnerabilities to natural hazards and climate change in coastal and marine areas, and 2) strengthen institutions for ICZM and empower civil society (including local communities) to engage in decision-making and management processes that affect the resilience of coastal ecosystems and livelihoods. The goal of MFF is conservation, restoration and sustainable management of coastal ecosystems as key natural infrastructure which support human well-being, resilience and security. MFF WIO aims at enhancing technical capacity at and across national levels which include the development of guidelines, study tours, regional training workshops/symposia and providing regional and international consultants to complement local expertise.
Annex 2 Trainer Biographies

Jared Bosire has a PhD in Marine Ecology and has worked at the Kenya Marine and Fisheries Research Institute for the last 17 years. He is currently the Assistant Director for the Marine and Coastal Research Division at KMFRI. His passion all the while has been on mangrove ecology and conservation ranging from restoration ecology, ecosystem functioning, resource assessment, human impacts on mangrove ecosystems and more recently climate change impacts. He has been a PI of many national and regional projects as well as lead technical expert/consultant e.g. Lead Consultant on Impacts of climate change mitigation and adaptation along the Kenyan and Tanzanian coasts awarded by the E. African Wildlife Society; Mangrove Expert in “Climate Change Impacts to Madagascar’s Biodiversity & Livelihoods” team advising the Malagasy government on climate change strategy, vulnerability assessments, mitigation and adaptation and Lead Consultant/technical expert in the World Wildlife Fund for Nature (WWF) Project on Coastal climate change mitigation and adaptation through REDD+ carbon programs in mangroves in Mozambique among others. Jared also led a WIO Mangrove Experts team in developing a state-of-the art model on the vulnerability of WIO mangroves to climate change and associated anthropogenic pressures, which will be published shortly. Additionally, Jared is the Coordinator of the WIO Mangrove Network.

James G. Kairo initiated his university career at the University of Nairobi, where he obtained BSc and MSc in Biology. He then obtained a PhD at the University of Brussels on the theme of ecology and restoration of mangrove systems. Kairo joined the Kenya Marine and Fisheries Research Institute in 1993. He currently leads a team of scientists dedicated to mangrove forestry research. He has vast working experience on the conservation, rehabilitation and sustainable utilization of mangrove resources, which has earned him two major awards. In 2002 he won the International Cooperation Prize awarded by the Belgian Government in recognition of his work on cooperation and sustainable development. In 2005 the Alcoa Foundation awarded him the WWF-Practitioner Fellowship. In addition, he has been awarded the Kenya’s Presidential Award of the ‘Moran of the Order of the Burning Spear (MBS) for his works on mangrove restoration and management. He has consulted for regional and international organizations, including; EAWLS, WWF, UNEP, and FAO. Dr Kairo is currently serving the global community as the: Member of Scientific Working Group on Blue Carbon; Lead Author, IPCC (2013) supplement on coastal wetlands, as well as a Panel member of the IUCN/Shell Niger Delta remediation.

Prof. K. Kathiresan is the Director of the Centre of Advanced Study in Marine Biology, Faculty of Marine Sciences, at Annamalai University. He has over 29 years of teaching experience and has published 390 papers, 7 books, and was contributed as one among the 19 global scientists to identify the globally threatened species of mangroves based on IUCN criteria in the year 2010. Dr. Kathiresan discovered a new plant species in the mangrove forest. This is the only endemic species of mangroves in India and it is named after his university as Rhizophora annamalayana Kathir. Additionally, Dr. Kathiresan developed
techniques for restoration of mangroves in degraded coast and demonstrated these techniques to work in the field along the south east coast – at Vellar estuary and in Pondicherry. He has received the Life Time Achievement Award for his contribution to marine microbiology, by Indian Association of Applied Microbiologists, Chennai.

**Mwita M. Mangora** is a Lecturer at the Institute of Marine Sciences of the University of Dar es Salaam in Tanzania. He teaches graduate courses on Applied Coastal and Marine Ecology, Conservation Science and Sustainable Utilization of Coastal and Marine Resources. Dr. Mangora is a forester and natural resources manager by profession. He specializes in Mangrove Ecology and Management; and Community Based Conservation. His current research focuses on mangroves stress ecophysiology, and impact of their transformations from both natural (especially climate change impacts) and anthropogenic pressures; assessment of mangrove ecosystems and their goods and services; and the impact on livelihoods of dependent communities; and restoration ecology and management. He also conducts studies on functional existence, management and socio-political-ecological impact of Marine Managed Areas including Marine Protected Areas. Dr. Mangora holds a B.Sc. in Forestry, M.Sc. in Management of Natural Resources and Sustainable Agriculture from Sokoine University of Agriculture and a Ph.D in Marine Sciences from University of Dar es Salaam, Tanzania.

**Jacob Ochiewo** is the Socio-economics Research Program Coordinator at KMFRI. He has 19 years of experience in socioeconomic assessments and monitoring, governance analysis, resolution of resource use conflicts, valuation of coastal resources/natural resource policy analysis, and integrated problem analyses. He has also been involved in a number of regional projects such as the UNEP WIO-LaB Project, the Agulhas and Somali Current Large Marine Ecosystems (ASCLME), ReCoMaP, Peri-Urban Mangrove Forests as Sewage Filters and Phyto-remediators in Eastern Africa (PUMPSEA), Integrated Problem Analysis for the African Process, Developing portfolio of projects for the African Process, Global International Waters Assessment, Vision and strategy development for WWF East Africa Marine Eco-region, and a number of WIOMSA MASMA funded projects. Nationally, he has played key roles in the development of management plans for the prawn fishery, ringnet fishery and mangroves, preparation of the state of the coast report for Kenya, conducting training on stakeholder analysis, stakeholder engagement, economic valuation of natural resources and identification of socio-economic and governance monitoring indicators.

**Melita Samoilys** has worked on coral reef research and management in the Indian and Pacific Oceans and in Sudan’s Red Sea since the early 1980s. Her particular areas of interest and experience are in fisheries, reproductive biology of groupers particularly spawning aggregations, coral reef fish diversity, marine protected areas, community – based coastal management and conservation and alternative livelihoods. She is co-Director of Coastal Oceans Research and Development – Indian Ocean (CORDIO) based in Mombasa, Kenya. CORDIO East Africa is a research organisation focused on conservation of marine and coastal ecosystems in the Western Indian Ocean. CORDIO specialises in generating knowledge to find solutions that benefit both ecosystems and people. Melita’s Doctorate is from James
Cook University, where she is Adjunct Associate Professor in the Dept of Marine Biology. She is a member of several international advisory bodies including two IUCN Species Specialist Groups: Groupers and Wrasses; Snappers Seabream and Grunts; the Institute for Water Environment & Health, United Nations University and the Marine Stewardship Council (MSC) Developing World Working Group.

**Hanneke Van Lavieren**, from the Netherlands, was born in Zambia and has spent most of her life in Africa and Asia. She completed her Masters degree in Marine Biology and Ecology in 1997 at the University of Groningen, the Netherlands. She began her career as a Fisheries Biologist for the Netherlands Institute for Fisheries Research where she studied catch composition and population dynamics of target and non-target fish species in the Dutch beam trawl fishery and alternative fishing methods to reduce by-catch. Longing to return to the tropics, she took up a position as (coastal/marine) Technical Advisor for a conservation project in the Philippines for the Netherlands Development Agency in 1999. Here she worked closely with local communities, conducted extensive coastal monitoring and training activities, and developed an integrated coastal management plan. In 2001, she moved to Kenya to join the United Nations Environment Programme, Regional Seas Programme, where she dealt with issues such as small islands, MPAs, coastal biodiversity, cetacean management, mangroves, climate change, and marine invasive species within 18 regional programmes. Since September 2006, she has been working for UNU-INWEH, and together with Dr. Peter Sale manages and coordinates coastal projects including work on mangrove ecosystems.

**Dr. Virginia Wang’ondu** is a researcher and a lecturer in Microbiology and Marine Botany at the School of Biological Sciences, University of Nairobi for the last nine years. She has vast experience in marine plant ecology specializing in mangrove phenology and productivity. She has worked both in the South and North coast regions of the Kenyan coast in collaboration with scientists at the Kenya Marine and Fisheries Research Institute (KMFRI, Mombasa) and Free University of Brussels (VUB). She is also involved in research and supervision of undergraduate and postgraduate research projects in Marine Ecology and Microbiology. She is currently a 2013 AWARD Fellow, a two year career development programme.
### Annex 3 Species List

#### Species Distribution Throughout Eastern and Southern Africa

<table>
<thead>
<tr>
<th>Species</th>
<th>Comoros</th>
<th>Kenya</th>
<th>Madagascar</th>
<th>Mauritius</th>
<th>Mayotte</th>
<th>Mozambique</th>
<th>Seychelles</th>
<th>Somalia</th>
<th>South Africa</th>
<th>Tanzania</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrostichum aureum</td>
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## Annex 4 National Statistics

### National Statistics for Eastern and Southern Africa (Spalding et al. 2010)

<table>
<thead>
<tr>
<th>Country or Territory</th>
<th>Land Area (Km²)</th>
<th>Total Forest Area (Km²)</th>
<th>Mangrove Area (Km²)</th>
<th>Age and Source of Area Statistic</th>
<th>No. mangrove species (excl. Introduced species)</th>
<th>Total Population (1000s)</th>
<th>Annual Population Growth</th>
<th>Rural Population (% of total)</th>
<th>GDP per capita (US$)</th>
<th>No. of protected areas with mangroves</th>
<th>Intl. protected areas</th>
<th>Spring tidal amplitude (m)</th>
<th>Average temp (Av. temp range) (˚C) (City)</th>
<th>Total rainfall (rainfall range) (mm) (City)</th>
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</thead>
<tbody>
<tr>
<td>Comoros</td>
<td>1860</td>
<td>50</td>
<td>1.17</td>
<td>2002 (FAO 2007)</td>
<td>7</td>
<td>614</td>
<td>2.4</td>
<td>64.4</td>
<td>361</td>
<td>1</td>
<td>2</td>
<td>25.3 (23.1-26.9) (Moroni)</td>
<td>2,700 (97-364) (Moroni)</td>
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<tr>
<td>Kenya</td>
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<td>35,220</td>
<td>609.51</td>
<td>2010 (Spalding et al. 2010)</td>
<td>8</td>
<td>32,447</td>
<td>1.7</td>
<td>59.5</td>
<td>343</td>
<td>11</td>
<td>2</td>
<td>26.3 (24.1-28.4) (Mombassa)</td>
<td>1,059 (15-240) (Mombassa)</td>
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<tr>
<td>Madagascar</td>
<td>581,540</td>
<td>128,380</td>
<td>2,991.12</td>
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<td>8</td>
<td>17,332</td>
<td>2.6</td>
<td>73.2</td>
<td>239</td>
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<td>1</td>
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<td>Mauritius</td>
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<td>1.20</td>
<td>2004 (FAO 2007)</td>
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<td>1,234</td>
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<td>56.5</td>
<td>4,289</td>
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<td>23.7 (21-26.3) (Plaisance)</td>
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<td>Mayotte</td>
<td>370</td>
<td>50</td>
<td>7.10</td>
<td>2010 (Spalding et al. 2010)</td>
<td>8</td>
<td>172</td>
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<td></td>
<td></td>
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<td>1</td>
<td>3.89 (Dzaoudzi)</td>
<td>25 (24-27)</td>
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<tr>
<td>Mozambique</td>
<td>784,090</td>
<td>192,620</td>
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<td>2001 (Fatoyinbo, 2008)</td>
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<td>19,129</td>
<td>1.8</td>
<td>63.2</td>
<td>270</td>
<td>6</td>
<td>1</td>
<td>3.65 (Maputo)</td>
<td>23.1 (Maputo)</td>
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<td>Seychelles</td>
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<td>400</td>
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<td>85</td>
<td>1.3</td>
<td>49.9</td>
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<td>Somalia</td>
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<td>2.93 (Mogadishu)</td>
<td>26.9 (25.8-28.5) (Mogadishu)</td>
<td>411.7 (0-80.5) (Mogadishu)</td>
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<td>South Africa</td>
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<td>45,584</td>
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<td>3</td>
<td>2</td>
<td>20.8 (16.6-24.6) (Durban)</td>
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<tr>
<td>Tanzania</td>
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<td>63.6</td>
<td>322</td>
<td>24</td>
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<td>3.9 (Mtwara) 4.31 (Zanzibar)</td>
<td>25 (23-27) (Tanga)</td>
<td>1,327 (33-278) (Tanga) 614 (47-401) (Zanzibar)</td>
</tr>
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