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Managing seagrasses for resilience to climate change

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Acknowledgements

Cover Photography

Front cover: Shallow seagrass beds in Chwaka Bay, Zanzibar, Tanzania; *Enhalus acoroides* in the foreground. Copyright: Sven Beer, Tel Aviv University.

Back cover: A fishing boat crosses a seagrass bed (*Enhalus acoroides*), Zanzibar, Tanzania. Copyright: Fred Short, University of New Hampshire.

Managing Seagrasses for Resilience to Climate Change

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About the IUCN Climate Change and Coral Reefs Marine Working Group

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

One of the outputs of this group was the setting up of a website that provides links to projects, events, partners and publications.

For more information, see http://www.iucn.org/news_events/events/congress/index.cfm

This publication is the 3rd in a series of publications on management tools to promote resilience in marine ecosystems. The other two, also available from IUCN's Global Marine Programme are listed below:

Coral Reef Resilience and Resistance to Bleaching
Gabriel D. Grimsditch and Rodney V. Salm
© IUCN/TNC, October 2006
Web link: http://data.iucn.org/dbtw-wpd/edocs/2006-042.pdf

Managing Mangroves for Resilience to Climate Change
Elizabeth Mcleod and Rodney V. Salm
© IUCN/TNC, October 2006
Web link: http://data.iucn.org/dbtw-wpd/edocs/2006-041.pdf

Table of Contents

1. Introduction

The sea star Protoreaster linckii *on the seagrass* Thalassia hemprichii *on an intertidal reef flat, Tanga, Tanzania. Copyright: J Tamelander/IUCN 2007*

There is growing evidence that seagrasses are experiencing declines globally due to anthropogenic threats (Short and Wyllie-Echeverria 1996, Duarte 2002, Orth et al. 2006). Runoff of nutrients and sediments that affect water quality is the greatest anthropogenic threat to seagrass meadows, although other stressors include aquaculture, pollution, boating, construction, dredging and landfill activities, and destructive fishing practices. Natural disturbances such as storms and floods can also cause adverse effects. Potential threats from climate change include rising sea levels, changing tidal regimes, UV radiation damage, sediment hypoxia and anoxia, increases in sea temperatures and increased storm and flooding events. Thus, seagrass meadows, the ecosystems that they support and the ecosystem services that they provide are threatened by a multitude of environmental factors that are currently changing or will change in the future.

Seagrasses are flowering plants that thrive in shallow oceanic and estuarine waters around the world. Descendants of terrestrial plants that re-entered the ocean between 100 and 65 million years ago, seagrasses have leaves, stems, rhizomes (horizontal underground runners) and roots. Although there are only about 60 species of seagrasses

worldwide, these plants play an important role in many shallow, near-shore, marine ecosystems.

Seagrass meadows provide ecosystem services that rank among the highest of all ecosystems on earth. The direct monetary outputs are substantial since highly valued commercial catches such as prawns and fish are dependent on these systems. Seagrasses provide protective shelter for many animals, including fish, and can also be a direct food source for manatees and dugongs, turtles, water fowl, some herbivorous fish and sea urchins. The roots and rhizomes of seagrasses also stabilise sediments and prevent erosion while the leaves filter suspended sediments and nutrients from the water column. Seagrass meadows are thus linked to other important marine habitats such as coral reefs, mangroves, salt marshes and oyster reefs.

This paper presents an overview of seagrasses, the impacts of climate change and other threats to seagrass habitats, as well as tools and strategies for managers to help support seagrass resilience.

Flatfish in seagrass, Cymodocea rotundata *and* Thalassia hemprichii*, behind the reef flat of a fringing reef of hard substrate mixed with sand, Tanga, Tanzania. Copyright: J Tamelander/IUCN 2007*

2 Overview of Seagrasses

This section gives a short overview of seagrasses: what they are and where they came from, and possible factors that could limit their growth and productivity under natural conditions.

Fact Box 1: Textbooks on Seagrasses

For more extensive background information about the biology and ecology of seagrasses, there are several textbooks available on the subject. These include (in chronological order):

The Seagrasses of the World by den Hartog (1970)
Seagrass Ecosystems: A Scientific Perspective edited by McRoy and Helfferich (1977)
Handbook of Seagrass Biology edited by Phillips and McRoy (1980)
Biology of the Seagrasses: A Treatise on the Biology of Seagrasses with Special Reference to the Australian Region edited by Larkum, McComb and Shepherd (1989)
Seagrass Ecology by Hemminga and Duarte (2000)
World Atlas of Seagrasses edited by Green and Short (2003)
Seagrasses: Biology, Ecology and Conservation edited by Larkum, Orth and Duarte (2006).

There is also a methods handbook entitled **Global Seagrass Research Methods** edited by Short and Coles (2001).

2.1 DEFINITIONS AND ORIGIN

Seagrasses are marine flowering plants (angiosperms); thus they live and complete their entire life cycle submerged in seawater (including underwater flowering, pollination, distribution of seeds and germination into new plants). Seagrasses also propagate vegetatively by elongating their rhizomes; a whole meadow may be one single clone resulting from one seedling. Both sexual reproduction and vegetative growth are critical to the propagation and maintenance of seagrass meadows (Hemminga and Duarte 2000).

Because they have roots, seagrasses can take up nutrients from the sediment (and are thus not restricted to the nutrient content of the seawater), which is beneficial especially in the often nutrient-poor waters of the subtropics and tropics. Sea-

grasses generally grow anchored in soft-bottom substrates due to their rhizomes and roots, and they usually do not "compete" with macroalgae for space because macroalgae grow mostly on rocky substrates.

The seagrasses are currently divided into 5 families: Hydrocharitaceae, Cymodoceaceae, Posidoniaceae, Zosteraceae and Ruppiaceae. Within those families are 12 genera, divided into some 60 species (although some species designations are in flux because of taxonomic disputes engendered by the relatively new tools of genetic analysis). About half of the species are tropical and half are temperate (Short et al. 2007). Although there are relatively few genera and species of seagrasses in the world as compared to other plant

Fact Box 2: The Origin of Seagrasses

Plants evolved first in the ocean and successfully invaded terrestrial habitats only some 300 million years ago. A few terrestrial plants then readapted to submergence in freshwater habitats, and from there "migrated" back into the ocean (e.g. Les et al. 1997). From those plants, seagrasses evolved some 100-65 million years ago. In addition to submergence, seagrasses have also evolved means to deal with the high salinities found in seawater. During their development as marine plants, seagrasses maintained both their vascular system (allowing them to transport nutrients between the roots and the leaves) and their ability to flower and produce seeds. Although many seagrass species look superficially alike, they are not a taxonomically unified group (den Hartog 1970, Green and Short 2003).

The development of different seagrass lineages occurred at least three different times during evolution (as determined by chloroplast DNA profiles, Les et al. 1997, Waycott et al. 2006). Seagrasses are a functionally similar group of plants (rather than a taxonomic group) that have adapted to survive in the world's coastal oceans, with different species featuring a range of tolerances to various marine environmental conditions.

groups (e.g. algae), extensive seagrass meadows occur along the coasts of every continent except Antarctica. Where present, they form the basis of many ecologically important marine habitats, supporting extensive biotic communities.

2.2 GENERAL BIOLOGY

Seagrasses represent the dominant component of many shallow marine habitats. Many seagrass meadows consist only of one seagrass species, although mixed stands containing up to 14 species may be found in the tropics, particularly in the Indo-Pacific region which has the highest seagrass biodiversity on earth (Short et al. 2007). Seagrass meadows are, on an area basis, very productive ecosystems with an average standing stock seagrass dry weight of 460 g per m² and an average growth rate of 5 g dry weight per m² per day (Duarte and Chiscano 1999).

The unique characteristics of seagrasses that differentiate them from other plants in the ocean are their leaves, roots and rhizomes and their reproductive organs for flowering, water-borne pollination and seed production. The shapes of

seagrass shoots vary from long, thin or strap-like leaf blades (up to 3 m long) to small, rounded paddle-shaped leaves (less than 1 cm long). The vegetative growth patterns of lateral branching and new shoot production often create dense meadows that form a canopy over the marine sediment. The plants' structure, as well as the height of the canopy and the extent of the

5 seagrass species, left to right: Enhalus acoroides, Cymodocea rotundata, Thalassia hemprichii, Halophila ovalis, and Cymodocea serrulata *in Palau.*
Copyright: Fred Short, University of New Hampshire

Fact Box 3: Transport of Nutrients and Gasses in Seagrasses

Seagrasses are vascular plants, the leaves of which are supported by the water column (or sometimes floating on the water surface or, in special cases, resting on the wet sediment at low tide). The roots and rhizomes attach the plants to the sediments, and their vascular and lacunal systems facilitate the transport and exchange of fluids and gasses, respectively. Nutrients are taken up from the sediments by the roots and transported to the meristems and leaves for growth; leaves themselves can also absorb nutrients, and are the main structures for absorbing CO_2 and other dissolved inorganic carbon forms (mainly bicarbonate ions, see section 3.5) from the seawater. Part of the O_2 that is produced in the leaves by photosynthesis (i.e. that part that does not diffuse out into the water column) is diverted to the lacunae in the leaves, and then diffuses through the rhizomes to the roots; some O_2 even diffuses out of the roots to maintain less hypoxic (with little O_2) conditions around the rhizosphere than if such transport did not take place. Seagrasses, typically growing in hypoxic or anoxic (O_2-free) sediments are thus totally dependent on transporting enough O_2 down to their roots to maintain aerobic respiration (and reducing sulphide formation outside of the roots, see Fact Box 4).

meadow, is influenced by a number of ecological factors such as water motion caused by currents and waves. Usually, the leaves are wider and weaker in areas with slow water motion, and narrower and more flexible where water movement is higher.

Since seagrasses are flowering plants that complete their whole life cycle under water, it follows that pollination occurs underwater too (although a few species form pollen that floats on the water surface). The seeds that are produced are important for the establishment of new patches and meadows, and in maintaining existing meadows, as well as providing genetic variability to existing habitats; this genetic variability is important in the ability of seagrasses to withstand environmental change (see section 3). The timing and details of seagrass sexual reproduction vary widely and are not well understood for many species (Walker et al. 2001).

Seagrasses continually produce new leaves, roots and rhizomes, while the old portions of the plants are shed and enter the detrital food web. For many species, the large turnover of leaf material represents a major organic input to detrital

pools in the sediment, while some of this organic matter is dispersed from shallow waters to the deep sea. Seagrass detritus also contributes to the formation of floating wrack (detached leaves and other seagrass parts) that often washes up on beaches. Regardless of its fate, seagrass detritus is a significant source of organic matter that fuels many animal and microbial food webs in the sea.

2.3 ENVIRONMENTAL BIOLOGY

Light is the ultimate abiotic factor controlling seagrass productivity and spatial distribution. The amount of light, or solar irradiance, reaching a seagrass meadow controls both daily growth and seasonal productivity, but is reduced by environmental factors such as water depth, turbidity, latitude and the state of surface ripples and waves. (See section 2.5 for a more detailed treatment of light effects on photosynthesis and growth.) Temperature and salinity are also important abiotic factors controlling seagrass production.

Temperature tolerances vary widely for temperate and tropical species. Although data for many species are lacking, it has been suggested that,

in general, temperatures exceeding 25°C adversely impact temperate seagrasses and those above 43°C impact tropical seagrasses (Biebl and McRoy 1971, Campbell et al. 2006, Diaz-Almela et al. 2007, Ehlers et al. 2008). Seagrasses survive in a range of salinities, from 5 PSU (practical salinity units, equivalent to parts per thousand,

ments, reduces turbidity by preventing resuspension, and prevents erosion (Hemminga and Duarte 2000). Seagrasses occur in both terrigenous or carbonate sediments containing a wide range of organic matter. Calcifying organisms such as coralline algae, molluscs and foraminifera, some of which grow between the seagrass shoots and

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Fact Box 4: Seagrasses Affect the Sediment

The high total organic inputs by seagrass plants and the trapping of organic material fuel sediment microbial activities, which are typically greater in seagrass meadows than in adjacent unvegetated sediments (Hemminga and Duarte 2000, Holmer et al. 2001). The microbial biochemical processes in the sediments use O_2, thus creating hypoxic conditions even in the upper sediment layers where seagrass rhizomes and roots are found. However, the O_2 that is generated in the leaves by photosynthesis, and which then diffuses through the lacunae towards the roots, is excreted into the sediment, thus forming relative oxygenation both inside the root tissues and in the rhizosphere that protects the roots from anoxic damage. It is also the microbially mediated interplay between hypoxic sediments and the relatively oxygenated plant rhizosphere that makes high concentrations of nutrients available to the seagrass roots.

When the transport of O_2 from shoots to the roots (see also Fact Box 3) is not enough to meet the demand for aerobic respiration, then submerged plants, including seagrasses, may switch to a fermentation pathway for short time periods (e.g. Smith et al. 1988). Thus, they may survive till the hypoxic stress is relieved, or will die if it is sustained (e.g. Perez et al. 2007). Sustained hypoxia or anoxia will also cause sulphide to be formed in the sediments. If the plant roots contain a low internal O_2 level, then this will enable the sulphide to enter the roots and this may lead to their death (Pedersen et al. 2004). When factors that negatively affect the O_2 production (e.g. low light) occur simultaneously with factors that increase the O_2 demand (e.g. increased organic loading of the sediments), there is an increased risk of sudden dramatic die-offs of seagrass communities, which will be accelerated by the even higher O_2 demand created when the dead plant material is degraded.

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ppt), to 60 PSU (Walker 1989), but some species (e.g. *Ruppia* spp.) can tolerate both lower (0 PSU) and higher salinities (140 PSU).

Most seagrasses are rooted in shallow sandy to muddy coastal sediments, although a few species (such as those of the genera *Phyllospadix, Amphibolis* and *Thalassodendron*) can grow on rocky substrates (den Hartog 1970, Hemminga and Duarte 2000). The extensive above- and below-ground structure of seagrasses traps sedi-

some as epiphytes, are important components of the meadows, contributing substantially to the formation of the carbonate sediments in which some seagrasses grow (Walker and Woelkerling 1988).

Seagrasses assimilate and cycle nutrients and other chemicals from both the sediment and the water column. Uptake of nitrogen (N) and phosphorus (P) from the sediment is an important source of nutrition, satisfying growth require-

ments in most highly-organic muddy environments. However, even in these rich sediments, seagrasses will preferentially accumulate nutrients from the water column (if present) via leaf uptake (Short et al. 1985). In nutrient-poor sediments, seagrass growth is often nutrient limited, with plants acquiring nitrogen (N) and phosphorus (P) from both the water column and the sediment (Short et al. 1993).

The primary production of seagrass meadows is a combination of seagrass leaf growth and that of micro- and macro-epiphytic and benthic seaweeds, with the latter groups occasionally contributing as much to the ecosystem production as the seagrass itself (Hemminga and Duarte 2000). In temperate regions, seagrass habitats and their animal communities integrate with other coastal habitats like salt marshes, kelp forests and bivalve reefs, while in the tropics critical links are with mangrove forests and coral reefs. Seagrasses provide habitats for rich faunal assemblages and seagrass meadows are recruitment and nursery areas for fish and crustaceans (Green and Short 2003). The "seagrass fauna" includes animals at many trophic levels, the most visible herbivores being dugongs, manatees and sea turtles in tropical, and swans and geese in temperate, waters. Seagrasses are also a direct food source for sea urchins and many species of fish (Pollard 1984, Heck and Valentine 1995). However, beyond direct consumption, seagrasses provide crucial food web resources for animals and for people. Particularly important are subsistence gleaning for protein on tropical coasts by villagers, nursery resources for commercially important finfish and shellfish species, and habitats for commercial and recreational bivalve fisheries.

Dugong in seagrass: Halophila stipulacea *bed, Red Sea, Egypt*
Copyright: SeagrassNet

2.4 DISTRIBUTION

Seagrasses are found throughout the world except in the waters of Antarctica (Green and Short 2003). The global seagrass coverage can presently be estimated to exceed 177,000 km² (Green and Short 2003). A more exact determination of the global extent of seagrasses is difficult because most seagrass meadows have not been mapped and the cost of comprehensive mapping is high.

marina, being the dominant species. The Temperate North Pacific is also dominated by *Zostera marina*, but is a region of higher seagrass diversity containing several *Zostera* species, as well as several *Phyllospadix* species in the surf zone. The Southern Oceans bioregion is a circum-global area including the temperate coastlines of Australia, Africa and South America, where extensive
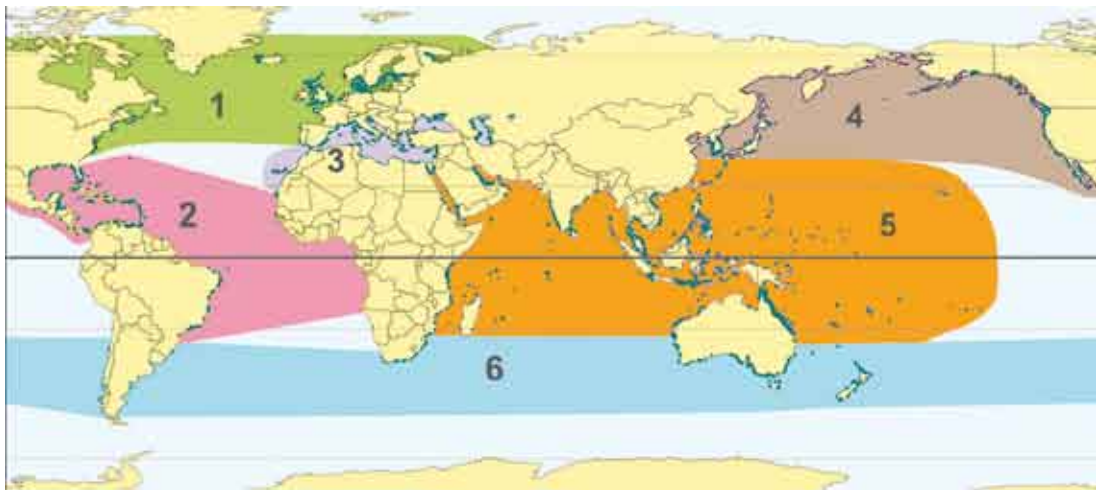
Global seagrass distribution shown as blue points and polygons and geographic bioregions: 1. Temperate North Atlantic, 2. Tropical Atlantic, 3. Mediterranean, 4. Temperate North Pacific, 5. Tropical Indo-Pacific, 6. Temperate Southern Oceans from Short et al. 2007.

The distribution of seagrass has been defined into six global bioregions (Short et al. 2007). The Tropical Indo-Pacific is the region of the highest seagrass biodiversity in the world, with many species often found in mixed meadows that have no clear dominant species. High species diversity is also found in the Tropical Atlantic bioregion, with *Thalassia testudinum* often dominating in clear waters. The three distinct temperate bioregions are: the Temperate North Atlantic, the Temperate North Pacific, and the Temperate Southern Oceans, with the Mediterranean bioregion having both tropical and temperate species. The North Atlantic Ocean has low seagrass diversity, with eelgrass, *Zostera*

meadows of low- to high-diversity temperate seagrass species are found. The clear waters of the Mediterranean Sea are dominated by *Posidonia oceanica* growing in vast meadows, but this bioregion also supports other temperate and several tropical seagrasses.

In both the northern and southern hemisphere, the global distribution of seagrass genera is remarkably consistent, with both hemispheres containing 10 genera and only one unique genus in each hemisphere. However, some genera have many more species than others, as evident in the multi-species genus *Halophila*. There are about the

same number of species in tropical and temperate bioregions. By far the most widely distributed seagrass is *Ruppia maritima*, which occurs in both tropical and temperate bioregions and in waters from fresh to hyper-saline.

Seagrass distribution patterns may change quickly as seagrasses respond to local environmental changes at the edges of the bioregions, where there are mixes of tropical and temperate species. Here, shifts in species composition will likely occur rapidly in response to global climate change. However, it is difficult to detect whether species composition shifts are caused by climate change impacts or by other human impacts.

2.5 GROWTH AND PRODUCTIVITY

Most seagrass stands begin as seedlings (although some begin from shoot propagules), and then spread through vegetative rhizome expansion and new shoot production until they form clonal patches, beds and, eventually, meadows. Some seagrass plants grow clonally for thousands of years (Reusch et al. 1999) and the clone can extend over many hectares of sea bottom. The growth rates of seagrasses have mostly been measured as leaf growth (Zieman 1974, Dennison 1990), but these leaf measurements seldom reflect the growth of the whole plant since they neglect growth of the underground rhizomes and roots (Short and Duarte 2001) and leaf maturation (Gaeckle and Short 2003). Seagrass growth methodology has now been refined to express whole plant growth by incorporating the growth of both above- and below-ground vegetative expansion, thereby initiating more realistic productivity metrics (Short and Duarte 2001). Variations in seagrass growth characteristics lead to wide species differences in growth strategies ranging from "pioneering" species that feature rapid vegetative expansion and new shoot production with little carbon storage (e.g. *Halodule* and *Halophila*

spp.) to "climax" species that spread slowly and build up large carbon reserves (e.g. *Thalassia* spp. and *Posidonia oceanica*). For Posidonia, extensive rhizome mats, which form under the living meadows, can be over 3000 years old (Mateo et al. 1997).

Propagules and seedlings : Posidonia australis *in Western Australia. Copyright: Gary Kendrick, University of Western Australia*

Being angiosperms, seagrasses also feature sexual reproduction and recent studies suggest that this is far more important than previously believed (reviewed by Walker et al. 2001). Flowering structures vary widely between species, from inconspicuous flowers at the sediment surface (e.g. *Halodule* spp.) to long flowering stalks extending into the water column well above the canopy (to heights of 8 m in *Zostera caulescens*, Lee et al. 2004). Since all species are water pollinated, they do not posses showy and colorful blooms. Seagrasses occur either as single sex plants (dioecious) or have both sexes on the same plant (moneocious), depending on species. Such varied reproductive strategies produce a broad range of recruitment success in

seagrass sexual reproduction. Mechanisms for the dispersal of seeds vary widely, from small hard-coated seeds released below the sediment surface (e.g. *Halodule*), through fleshy pre-germinated seeds that are expelled from a fruit (e.g. *Thalassia* and *Enhalus*) to viviparous seedlings that develop on the parent plant before dispersal (e.g. *Amphibolis* and *Thalassodendron*). Apart from these various flowering and seed setting strategies, the success of recruitment through

sexual reproduction extends from prolific (*Ruppia maritima* and *Halophila decipiens*) to marginal (some *Posidonia* species), but the importance of recruitment success is still largely unknown for many seagrasses.

As for all other plants, photosynthesis is the basic process that underlies the growth and productivity of seagrasses. However, unlike macroalgae, the products of photosynthesis (principally sucrose)

Fact Box 5: Light and Photosynthesis

Light is an obvious limiting factor both for the vertical distribution of a seagrass along a depth gradient and for its growth in a specific habitat. Again, since seagrass photosynthesis must support also non-photosynthetic underground tissues, it follows that seagrasses have a higher minimum light requirement for growth than macroalgae. It has been estimated that seagrasses need more than 10% of the surface irradiance (Duarte 1991), i.e. >200 µmol photons m^{-2} s^{-1} during cloudless middays, in order to survive (while most algae need only 1% of the surface light). Thus, the depth limit for seagrass growth is largely determined by light penetration through the water, restricting seagrasses to the continental margins of the oceans to depths less than 70 m (Short et al. 2007). However, in many parts of the world, particularly near large river discharges or areas of human development, seagrass depth limits are reduced by significant light attenuation. Even in shallow waters, specific habitats can feature very low irradiances because of cloudy weather and strong light attenuation. In less clear waters, seagrasses form less dense canopies so as to avoid self-shading (Short et al. 1995, Collier et al. 2008), and may also produce elongated leaves that reach the light nearer to the surface. During cold seasons, seagrasses in temperate areas can survive at very low irradiances, presumably by utilising carbohydrate reserves stored in the rhizomes during the summer.

High irradiances, such as found in the tropical intertidal, can also limit the growth and production of seagrasses by causing photoinhibition, which lowers photosynthetic rates. In some cases, however, intertidal seagrasses can protect their photosynthetic mechanism from damage due to high irradiances during low tide by processes resulting in non-photochemical quenching (Beer and Björk 2000) or by clumping together their chloroplasts during midday so that they shade one another (Sharon and Beer 2008). There is also a reduction in photosynthetic rates by desiccation per se, at least in the tropical intertidal (Björk et al. 1999), which, together with photoinhibition, may be detrimental for some seagrasses under periods of extreme low tides.

Seagrasses can use bicarbonate ions (HCO_3^-, which are present in seawater at a much higher concentration than CO_2) as a major source of inorganic carbon for their photosynthetic needs (Beer et al. 2002). However, it has been considered that they do so less efficiently than macroalgae (e.g. Beer and Koch 1996), such that they are not saturated with inorganic carbon in today's atmosphere-equilibrated shallow coastal oceanic habitats where they grow. This previously general notion of inorganic carbon-limitation was supported by the experimental finding that e.g. the temperate *Zostera marina* showed higher growth rates under, at least short-term, CO_2 enrichment (Thom 1996) while long-term effects were less clear (Palacios and Zimmerman 2007). The extent of inorganic carbon limitations for seagrass photosynthesis is still unclear, and experimental studies on two tropical species have indicated that they may be inorganic carbon-saturated in their natural habitats (Schwarz et al. 2000). However, for at least some seagrass species, increased CO_2 may increase overall seagrass production (Orth et al. 2008).

Thalassodendron ciliatum in Mombassa, Kenya: flowering shoot with viviparous seedling.
Copyright: Fred Short, University of New Hampshire

must in seagrasses support not only their above-ground tissues but also their underground roots and rhizomes (and the latter can have a biomass exceeding that of the shoots). Thus, seagrasses must in principle photosynthesise more than e.g. macroalgae in order to support the growth of the entire plants. On the other hand, the roots of seagrasses aid them in the uptake of nutrients; thus, seagrasses can thrive in nutrient-poor waters provided that the substrate is rich in nutrients. What, then, is the limiting factor for the growth and productivity of seagrasses as based on their photosynthetic rates? Under natural conditions, light, salinity, the inorganic carbon source, nutrient availability and temperature can all limit the growth rates of seagrasses.

Nutrients are another potentially limiting factor for seagrass growth. Typically in the tropics (Terrados et al. 1999, Ferdie and Fourqurean 2004), and also in some temperate areas, N is limiting, and P can be limiting in fine carbonate sediments (Short et al. 1990, Short et al. 1993). Iron (Fe) is another potentially limiting nutrient (Duarte et al. 1995). The discussion on N and P (or another nutrient) as limiting seagrass growth is complicated by local nutrient regimes (Alcoverro et al. 1997) and by the large excess of nutrients that are discharged into

many coastal waters which eliminates nutrients as a limiting factor in many areas (Short and Wyllie-Echeverria 1996). Since many tropical seagrasses are nutrient limited in nature, nutrient release from degrading organic material in the sediment may increase their productivity. However, when sediment organic material increases substantially as a result of e.g. pollution, this may lead to O_2 depletion in the sediments and, accordingly, reduced seagrass growth.

2.6 BENEFITS OF SEAGRASSES

Seagrasses have had many traditional uses (cf. Terrados and Borum, 2004). They have been used for filling mattresses (with the thought that they attract fewer lice and mites than hay or other terrestrial mattress fillings), roof covering, house insulation and garden fertilisers (after excess salts were washed off). They have also been used in traditional medicine in the Mediterranean (against skin diseases) and in Africa (Torre-Castro and Rönnbäck 2004). Seagrass seeds of several species are sometimes used as a food source.

Fishermen in seagrass, Bali, Indonesia.
Copyright: Fred Short, University of New Hampshire

Graduate student snorkeling over a New Hampshire Zostera *marina bed.*
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While only a few larger animals possess the ability to actually digest seagrass leaves (dugongs, turtles, geese, brant, and some herbivorous fish), the leaves often harbour a multitude of organisms such as algae and invertebrates, which serve as food for transient fish, as well as the permanent fauna within the seagrass meadow. Seagrass habitats also provide shelter and attract numerous species of breeding animals. Fish use the seagrass shoots as a protective nursery where they, and their fry, hide from predators. Likewise, commercially important prawns settle in the seagrass meadows at their post-larval stage and remain there until they become adults (Watson et al. 1993). Moreover, adult fish migrate from adjacent habitats, like coral reefs and mangrove areas, to the seagrass meadows to feed on the rich food sources within the seagrass meadows (Unsworth et al. 2008). Many small subsistence fishing practices, such as those in Zanzibar (Tanzania), are totally dependent on seagrass meadows for their fishing grounds (Torre-Castro and Rönnbäck 2004); coastal populations in such areas receive most of their protein from fishing within such meadows.

One of the most conspicuous contributions of seagrasses is their sediment trapping and sediment binding capacities. The leaves act as a trap for suspended materials that are brought to the seagrass meadows with the currents. Thus, seagrasses clear the water of these materials. The extended rhizome and root systems stabilise the sediments and prevent them from being re-suspended. Seagrasses may thus prevent coastal erosion, especially following heavy winds, rains and floods. Another physical benefit of seagrasses is their ability to attenuate waves, thereby protecting shores from erosion (Koch 2001). The removal of seagrasses can thus lead to increased shoreline erosion.

Another function of seagrasses is their oxygenation of otherwise hypoxic sediments (see Fact Box 4), providing O_2 to sustain high microbial activity within

Sampling seagrasses in Madagascar, Thalassodendron ciliatum *meadow, Madagascar. Copyright: Fred Short, University of New Hampshire*

the sediments, which in turn allows nutrients to be efficiently recycled from dead organic matter.

Seagrasses can also constitute an important carbon sink due to their slow rate of decomposition. For example, the rhizomes of *Posidonia oceanica* in the Mediterranean form a deep organic mat that can be thousands of years old and several metres thick, Mateo et al. 1997. It has been estimated that

carbon fixation of seagrasses constitutes up to 1% of the total carbon fixed in the oceans but that these plants store 12% of the ocean carbon (Duarte and Cebrian 1996) e.g. in such mats. Thus, seagrass meadow diebacks may speed up the CO_2 release globally.

In addition to their many other benefits, seagrass meadows also have a high economic value. For example, their value for prawn fisheries in Queensland (Australia) has been estimated at $AU 1.2 million per year (Watson et al. 1993). In all, the value of marine macrophyte (macroalgae and seagrasses) ecosystems has been estimated at $US 19,000 per hectare per year (Costanza et al. 1997), a value 33 and 23 times higher than average oceanic and terrestrial values, respectively, and is 3 times more than coral reefs and 10 times more than tropical forests.

Finally, seagrasses have aesthetic values; they form beautiful green "oases" on shallow soft bottoms, and it is pleasant to snorkel or dive above seagrass meadows and observe their conspicuous fauna.

3   Disturbances to Seagrass Systems

Seagrass bed, Thalassia hemprichii*, covered with green algae, Tanga, Tanzania. Fast-growing algae can smother seagrasses as well as corals. Copyright: J Tamelander/IUCN 2007*

Human development can alter coastal ecology, often resulting in loss of seagrass habitats. Extensive losses, especially in developed and densely populated areas have been documented. An estimated 65% of *Zostera marina* in industrial parts of the northwest Atlantic was lost since the time of European settlement (Short and Short 2003). In other examples, 5000 hectares of seagrass meadows disappeared during the development of the rural area of Adelaide, Australia (Westphalen et al. 2004) and 58% was lost along the Swedish west coast over the last two decades (Baden et al. 2003).

Natural disturbances may also impact seagrass ecosystems (Short and Wyllie-Echeverria 1996). An extreme but natural loss of seagrass was the "wasting disease" of *Zostera marina* (eelgrass), which almost disappeared from both sides of the North

Atlantic in the 1930s (Short et al. 1988, den Hartog 1989). The pathogen that caused this dieback was a slime mold (*Labyrinthula zosterae*, Short et al. 1987, Muehlstein et al. 1988). A recurrence of this disease in the United States destroyed much of the eelgrass in the Great Bay Estuary (New Hampshire) in the 1980s (Short et al. 1987, Short and Short 2003). Similarly, but to a lesser extent, a mass mortality of the seagrass *Thalassia testudinum* in Florida Bay (Robblee et al. 1991) may also have been linked to the spread of the pathogen *Labyrinthula* sp., possibly preceded by hypoxia in the sediment. While it is possible that such catastrophic events could be triggered, or enhanced, by human-induced environmental change causing eutrophication (Burdick et al. 1993, Harwell and Orth, 2002), fluctuating salinity (Grillas et al. 2000) and global warming (Harvell et al. 2002), no such causes have been proven.

Other natural phenomena such as grazing of seagrasses have also been suggested to interact with anthropogenic disturbances. Overgrazing of seagrasses by sea urchins may be triggered by reduced predation by fish (which were decimated by overfishing) and eutrophication. In severe cases, such overgrazing could decimate entire seagrass meadows (Eklöf et al. 2008).

3.1 Anthropogenic Non-Climate Related Impacts

The two largest human impacts to seagrasses worldwide are sediment loading and eutrophication. Eutrophication is a problem most common in heavily developed parts of the world. In the tropics, human-produced sedimentation and suspended sediments from watershed, deforestation and mangrove clearing have the greatest environmental impact on seagrasses (Terrados et al. 1998, Duarte et al. 2008). Removal of terrestrial vegetation leads to erosion and transport of sediments through rivers and streams to estuaries and coastal waters, where the suspended particles create turbidity that reduces water clarity and eliminates seagrass growth and development. Cutting and clearing of mangroves to create aquaculture ponds for shrimps increase sediment-rich runoffs, re-suspension and erosion, also leading to lower seagrass survival. All these discharges into tropical areas have major impacts on water clarity, thus reducing the light available to seagrasses.

Increased nutrient levels in the water column of oligotrophic waters stimulates the growth of phytoplankton, macroalgae (also called seaweeds) and epiphytic algae, as well as the seagrasses. Thus, nutrient additions can often lead to seagrasses being outcompeted by a heavy overgrowth of macroalgae (Short et al. 1995). In Western Australia, heavy epiphyte fouling, probably due to nutrient-rich effluents, likely caused extensive seagrass losses (Cambridge et al. 1986). Light reductions from increased turbidity following eutrophication were suggested to cause large-scale seagrass declines in Florida Bay,

U.S. (Hall et al. 1999). Nutrient enrichment can also occur naturally (e.g. in the Gulf of Aqaba, Red Sea) as nutrient-rich waters well up during a seasonal mixing. If the nutrient addition is moderate, then both the algal epiphytes that grow on the seagrasses and the seagrass shoot productivity may increase (Uku and Björk 2005). The benefit of increased nutrient availability stimulates especially those seagrasses that are growing in high-light environments. When the nutrient input is higher, then massive growth of both epiphytic and benthic macroalgae (Rabalais and Nixon 2002, Smith 2003) and/or phytoplankton may cause such a strong shading of the seagrass leaves that seagrass productivity decreases, and the plants may die (Short and Burdick 1996, Tomasko et al. 2001, Tamaki et al. 2002). With decreasing seagrass productivity, O_2 levels in the sediment decrease and sulphides may form so that roots die (e.g. Perez et al. 2007) and, ultimately, so does the entire meadow.

Although less common, effects of increased nutrient levels in the water column other than through decreased light have also been reported. For example, eutrophication by fish farm effluents may cause reductions in rhizome growth and, thus, in the extent of the meadows for reasons other than light reduction (Marba et al. 2006). In another case, declines in the size of meadows in the vicinity of fish farms could not be explained by increased epiphyte cover or decreases in light (but possibly due to overgrazing due to an increased palatability of the epiphyte tissues and increased hypoxia in the sediments, Ruiz et al. 2001).

Experiments have shown that heavy metals such as copper and zinc, petrochemicals and herbicides have negative effects on seagrass photosynthesis (Macinnis-Ng and Ralph 2002, 2003a, 2003b, 2004). However, no negative effects on productivity could be shown in areas of high *in situ* levels of zinc, lead and cadmium (Hoven et al. 1999, Marie-Guirao et al. 2005). In all, too little data are available in order to evaluate the effect of these potential pollutants on seagrasses in nature.

Physical removal can have more drastic and long-lasting effects on climax-species of seagrasses than on pioneering ones. This is because seagrass meadows of climax species are long-lived and stable (Duarte et al. 2006, Gullström et al. 2006) but recover and proliferate slowly. Pioneering species, on the other hand, are more easily damaged by physical disturbances, but may rebound more quickly if environmental conditions favour re-growth (Kenworthy et al. 2002). Removal of seagrasses can be either intentional or unintentional: Seagrasses have been intentionally removed by hotels in the belief that they were unattractive to tourists. As a result, turbidity increased and there was a total loss of the sediment infauna (Daby 2003). A frequent cause for seagrass removals is the dredging and filling activities required for the building of causeways and harbours (e.g. Ruiz and Romero 2003). Also smaller scale uprooting and shading of seagrasses by moorings (Hastings et al. 1995), dock construction (Burdick and Short 1999) and boat anchoring may cause declines in seagrass meadows. Another activity that has severely decimated seagrass is trawling and other destructive fishing methods (Neckles and Short 2005).

3.2 POTENTIAL CLIMATE CHANGE IMPACTS

Global climate change refers to the complex environmental changes caused by increasing emissions of CO_2 and other greenhouse gasses to the atmosphere, and they have great consequences for marine life forms (see e.g. Harley et al. 2006). The different components of global change that may affect seagrass habitats are discussed below.

CO_2: The atmospheric CO_2 concentration has increased from 280 parts per million (ppm) in 1880 to nearly 380 ppm in 2005, even though about 30% of all atmospheric CO_2 resulting from burning of fossil fuels has been taken up by the ocean (IPCC 2007). The most basic consequence of increasing atmospheric CO_2 levels on seagrasses is its possible direct positive effect on photosynthesis and growth.

Increasing atmospheric CO_2 concentrations, resulting in a corresponding increase in oceanic CO_2 levels, may cause seagrass production to increase since seagrasses at times are carbon limited. However, experimental evidence for increased seagrass productivity as a response to elevated CO_2 levels is inconclusive. In a short-term experiment, *Zostera marina* was found to grow at increasing rates under CO_2 enrichment (Thom 1996). On the other hand, in a long-term experiment, there was no effect of increasing CO_2 levels on the above-ground productivity of *Zostera marina* (Palacios and Zimmerman 2007). Higher CO_2 levels may also increase the production and biomass of epiphytic algae on seagrass leaves, which may adversely impact seagrasses by causing shading. Thus, changes may occur in the competition between seagrass species and between seagrasses and algae (Beer and Koch 1996).

pH: Concomitantly with increased dissolved CO_2 levels, the pH of oceanic waters will decrease. This is because CO_2 in solution forms an equilibrium with carbonic acid, which dissociates to add

*Fishers harvesting clams from an aquaculture lease in a seagrass bed (*Zostera japonica *and* Halophila ovalis*) in Bei Hai, China.*
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protons to the water (thus a lower pH). This, in turn, has an effect on the relative concentrations of the other dissolved inorganic carbon forms in seawater. However, since CO_2 is used by seagrasses at a higher affinity than HCO_3^-, the relatively reduced HCO_3^- content of the seawater at lower pH values would not impede photosynthesis or counteract the positive effect of increasing CO_2 levels (Beer et al. 2006a). Seagrasses have been shown to raise pH values in dense stands or in isolated pools up to 9 (Beer et al. 2006b). At such high pH values, seagrasses are close to their upper limit of inorganic carbon uptake, and photosynthetic rates are therefore lowered. Under increased CO_2 concentrations in the future, the acidification of seawater could counter the high pH formed by photosynthesis in such dense seagrass stands, thus increasing seagrass photosynthesis and productivity.

Temperature: Since 1880, the earth has warmed 0.6-0.8°C (Houghton et al. 2001), and it is projected to warm between 2-4°C by 2100, mostly due to human activity (IPCC 2007). Similar increases have been predicted for marine systems (Shep-pard and Rioja-Nieto 2005). Temperature stress on seagrasses will result in distribution shifts, changes in patterns of sexual reproduction, altered seagrass growth rates, metabolism, and changes in their carbon balance (Short et al. 2001, Short and Neckles 1999). When temperatures reach the upper thermal limit for individual species, the reduced productivity will cause plants to die (Coles et al. 2004). Elevated temperatures may increase the growth of competitive algae and epiphytes, which can overgrow seagrasses and reduce the available sunlight they need to survive. The response of seagrasses to increased water temperatures will depend on the thermal tolerance of the different species and their optimum temperature for photosynthesis, respiration and growth (Neckles and Short 1999). For tropical seagrasses, it was suggested that the photosynthetic mechanism becomes damaged at temperatures of 40-45°C (Campbell et al. 2005). High temperatures have likely caused large scale diebacks of *Amphibolis antarctica* and *Zostera* spp. in southern Australia (Seddon et al. 2000). For the temperate *Zostera marina*, experiments showed that a 5°C increase

*Cymodocea rotondata with red leaves from UV blocking pigments, Hainan Island, China.
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Fact Box 6: Responses to UV Radiation

The production of UV-blocking compounds by seagrasses as protection from harmful radiation requires expenditure of plant resources that may adversely impact the plants. The responses of seagrasses to UV-B radiation will vary by species and can possibly result in purple coloration of seagrass leaves (Short, personal observation). Laboratory experiments indicate that *Zostera capricorni*, *Cymodocea serrulata* and *Syringodium isoetifolium* are UV-tolerant and are able to adapt to increasing UV by producing blocking pigments (Dawson and Dennison 1996). Other studies show that photosynthesis of *Halodule wrightii* has a high tolerance to UV-B, *Syringodium filiforme* has moderate tolerance, and *Halophila engelmanni*, *Halophila ovalis* and *Halodule uninervis* have a very low tolerance (Dawson and Dennison 1996, Short and Neckles 1999). Hader (1993) also observed some evidence that epiphytic growth on seagrasses may shield them from UV-B.

in the normal seawater temperature caused a significant loss in shoot density; however, it seemed that a high genetic diversity within the meadows increased its possibility to recover from such extreme temperatures (Reusch et al. 2005, Ehlers et al. 2008). At the margins of temperate and tropical bioregions (Short et al. 2007), and within tidally restricted embayments where plants are growing at their physiological limits, increased temperature will result in losses of seagrasses and/or shifts in species composition. Seagrass distribution and abundance may also be altered through the effects of increased temperature on flowering and seed germination (de Cock 1981, McMillan 1982, Phillips et al. 1983, Durako and Moffler 1987).

Near a Palau river mouth, Enhalus acoroides *is coated with sediment after a heavy rain storm event.*
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Light and UV radiation: Global climate change may bring about changes in radiation. On the one hand, altered weather patterns may cause more clouds to form, thus reducing the photosynthetically active radiation (PAR) of visible light. This may then be detrimental to those seagrass meadows that already grow close to their low-light limit. In a related condition, if the trend of increased UV radiation continues (because of diminishing ozone levels), then shallow growing seagrasses would suffer its detrimental effects.

Storms: Climate change may be causing tropical storms to increase in intensity (IPCC 2007) and possibly in frequency (Trenberth 2005), although there is tremendous uncertainty in these predictions and there is no scientific consensus thus far. Such storms in coastal areas may cause massive sediment movements that can have disastrous effects on seagrass meadows by uprooting or burying of the plants (Short et al. 2006). The increased turbidity caused by storms can remain long after the storm subsides, causing shading-out of the plants. Increases in rainfall and discharges from rivers can increase sediment loading, which may also result in decreased light levels or smothering of seagrasses. Some 1,000 km^2 of seagrasses in Queensland, Australia, were lost by uprooting and/or sediment disturbances after two major floods and one cyclone within 3 weeks (Preen et al. 1995). Since climax seagrass species are relatively slow-

growing plants that need to establish extensive root systems in order to anchor themselves in the sediment, frequent storm events may prevent their reestablishment. In deeper waters, the increased turbidity caused by storms may cause drastic declines in seagrass growth in already light-limited systems.

Floods: Extreme changes in weather patterns may also cause flooding, which in turn causes decreased irradiances both because of the deeper water and the increased turbidity and rate of sedimentation. For example, seagrass species richness and leaf biomass in the Philippines and Thailand declined sharply when the silt and clay content of the sediment exceeded 15% (Terrados et al. 1998). Currently, extreme flooding events have become increasingly common in Eastern Africa, and have been shown to cause large-scale losses of seagrass habitats (Bandeira and Gell 2003). Similarly, seagrasses in Queensland, Australia, were lost in a catastrophic flooding event, and it took three years for them to recover (Campbell and McKenzie 2004). Also, heavy rains may adversely affect seagrasses by diluting the seawater to a lower salinity. The effects of such an extreme rain event caused a slow recovery of *Thalassia testudinum* in Venezuela (Chollett et al. 2007).

Sediment hypoxia and anoxia: While anoxia constitutes a major potential disturbance in coastal waters that can lead to large scale mortality of most benthic life forms (Kemp et al. 1992, Viaroli et al. 2001), seagrasses are more sensitive to sediment anoxia than e.g. macroalgae since their growth depends on the wellbeing of a healthy extensive root system within the sediment. Most sediments are naturally hypoxic, and seagrasses have the ability to transfer O_2 from the shoots to the roots and so counteract the otherwise negative effects of hypoxia. On the other hand, any disturbance that lowers the light (e.g. storms and floods) will likely reduce photosynthesis and, accordingly, the seagrass leaves will form less O_2 for transport towards the root system. Prolonged cases of anoxia often lead to the formation of sulphides in the sediment, which is poisonous to seagrasses (e.g. Borum et al. 2005)

and can lead to plant death. Also, increased temperatures cause more rapid respiratory breakdown of organic matter in the sediment, exacerbating O_2 deficiencies and enhancing anoxic stress.

Sea level rise and altered currents: With future global warming, there may be a 1-5 m rise in the seawater levels by 2100 (taking into account the thermal expansion of ocean water and melting of ocean glaciers, Overpeck et al. 2006, Hansen 2007, Rahmstorf 2007). Rising sea levels may adversely impact seagrass communities due to increases in water depths above present meadows (thereby reducing light), changed currents causing erosion and increased turbidity and seawater intrusions higher up on land or into estuaries and rivers (favouring land-ward seagrass colonisations, Short et al. 2001). Changing current patterns can either erode seagrass beds ("beds" are often used in this text synonymously to "meadows", but may indicate comparatively smaller entities) or create new areas for seagrass colonization. On the positive side, increases in current velocity within limits may cause increases in plant productivity (see Fact Box 9) reflected in leaf biomass, leaf width, and canopy height (Conover 1968; Fonseca and Kenworthy 1987, Short 1987).

Seagrass diversity: Enhalus acoroides *(large) and* Halophila ovalis *(very small) in Guam.*
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3.3　Possible Adaptations to Environmental Change

The term adaptation implies adjustments to long-term continuous changes in the environment such as caused by global change. Under changing environments, genetically diverse seagrass populations have a higher chance of success than do genetically conserved ones. Indeed, it was experimentally shown that genetic diversity in the temperate *Zostera marina* could help the plants to cope better with high summer temperatures (Ehlers et al. 2008), and the same can be expected also for tropical species. It has been shown that evolutionary change in a species can occur within a few generations (Rice and Emery 2003), thus making it possible for seagrasses to cope if the changes occur at a slow enough rate to allow for adaptation. Another possible adaptation to global warming is based on the fact that different species show different temperature tolerances. Thus, those species within a mixed-species meadow that show a higher tolerance to increased temperatures will have a better chance of survival making it possible for the meadow to remain functioning (albeit with an altered species composition). Such reasoning may apply to other climate impacts as well.

Fact Box 7:　How to Identify Threats to Seagrasses

Threats to seagrass meadows may be identified by monitoring the following parameters:

Growth and Productivity: One of the most direct early warnings for declining seagrass meadows is a decrease in growth and productivity, which can be monitored using e.g. the methods described by Short and Duarte (2001, Chapter 8 in Short and Coles, eds., Global Seagrass Research Methods). As discussed above, an indication of seagrass productivity is reflected in their photosynthetic rates. Such rates can be measured either as O_2 or CO_2 gas exchange, or as electron transport rates (Beer, Björk, Gademann and Ralph 2001, Chapter 9 in Short and Coles, eds., Global Seagrass Research Methods).

Abiotic Parameters – Light: Among the abiotic (non-biological) parameters that are most tightly coupled with seagrass growth is light (or irradiance). This is because under certain levels, the seagrass plants will respond with negative photosynthetic gas exchange, growth and productivity. Reasons for declining irradiances can be increased turbidity or above-water structures such as causeways, etc. See e.g. Carruthers, Longstaff, Dennison, Abal and Aioi (2001, Chapter 19 in Short and Coles, eds., Global Seagrass Research Methods) for various measurements of light penetration in seagrass areas.

Abiotic Parameter – Others: Water movement is essential for the growth and wellbeing of seagrasses. This is because both nutrients and CO_2 (and other inorganic carbon forms) diffuse slowly through water, and need to be brought to the leaves by mass transport. On the other hand, too strong water movement may cause disruptions of the plants (including uprooting). For methods to measure water movements, see Koch and Verduin (2001, Chapter 17 in Short and Coles, eds., Global Seagrass Research Methods). Other abiotic parameters such as nutrient loads and temperature should be monitored too, as should some other aspects of water quality (see Granger and Izumi 2001, Chapter 20 in Short and Coles, eds., Global Seagrass Research Methods).

Sediment Parameters: It is becoming increasingly clear that the sediment structure and composition has a high importance for seagrass growth and survival. Therefore, any seagrass monitoring programme should include measurements of various parameters pertaining to the seagrass meadow sediments. For this, see Erfemeijer and Koch (2001, Chapter 18 in Short and Coles , eds., Global Seagrass Research Methods).

4 What Can Managers Do?

Jellyfish over Enhalus acoroides *meadow, inner near-shore, Tanga, Tanzania.*
Copyright: J Tamelander/IUCN 2007

Seagrasses are experiencing a worldwide decline due to a combination of climate change impacts and other anthropogenic factors. Seagrass areas along coastlines that are already affected by human activities (causing e.g. sedimentation, nutrient enrichment, eutrophication and other environmental destruction) are most vulnerable to climate change impacts. Mitigating strategies (e.g. limiting greenhouse gas emissions) that affect the rate and extent of climate change impacts should be coupled with resilience-building adaptation strategies (Johnson and Marshall 2007). Managers can promote policies that protect and conserve seagrasses, while also assisting in mitigation efforts by raising awareness about the vulnerability of seagrass habitats to coastal impacts. Managers can also contribute knowledge about climate change impacts on tropical and temperate marine ecosystems to help set mitigation targets (Johnson and Marshall 2007).

Management strategies that enhance the resilience of seagrasses must be developed and implemented to ensure the survival of these valuable habitats. While there is little that managers can do to control large-scale stressors at their sources, there are other actions they can take to help seagrasses survive catastrophic climate-related events. Managers can thus play a crucial role in ensuring that seagrasses survive climate change challenges by taking appropriate actions that begin to reduce major impacts. These are:

a) Improve management to reduce human impacts and to maintain seagrasses in as healthy a condition as possible and so better able to resist or recover from stresses, including climate change. There is no substitute for effective management and good water quality to enhance seagrass resilience.

b) Develop baseline maps of seagrass meadows to allow for monitoring of changes in distribution and abundance.

c) Implement monitoring programmes (e.g. SeagrassNet, see section 5) that provide feedback on the results of coastal management. If management strategies are not meeting their objectives, they need to be adapted to achieve their goals.

d) Identify and fully protect seagrass communities that are at low risk of succumbing to climate change and anthropogenic impacts because these seagrass communities will serve as refugia to help seed the recovery of damaged areas.

e) Reduce the risk of any seagrass communities being lost as a consequence of climate change impacts by protecting multiple samples of the full range of seagrass communities and from a wide geographical range.

f) Identify patterns of connectivity between seagrass beds and adjacent habitats, e.g. mangroves and coral reefs, to improve the design of marine protected area networks and allow for ecological linkages and shifts in species distribution.

g) Restore critical seagrass areas that are positioned to survive climate change impacts by eliminating the causative agents of their decline.

h) Raise awareness of the value and threats to seagrasses, ensuring that coastal zone management or land use policies and plans address potential impacts to seagrasses and implement codes of conduct for fishing and boat anchoring to reduce disturbances.

Fact Box 8: Examples of Major Seagrass Losses - Part 1

Documented catastrophic losses of seagrasses, from both natural and human-caused impacts, include some which may be climate-change related (based on data from Short and Wyllie-Echeverria 1996 and Green and Short 2003).

Area	Cause	Time	Extent
North Atlantic	Wasting disease	1930s	90% eelgrass loss in 5 years
Prince William Sound, AK, USA	Earthquake	1960s	Local loss in uplift areas
Chesapeake Bay, USA	Water quality	1970s	Massive eelgrass decline
Great Bay, NH, USA	Wasting disease	1980s	80% eelgrass loss in 2 years
Waquoit Bay, MA, USA	Nitrogen loading	1980s	85% eelgrass loss in 6 years
Florida Bay, USA	Unknown	1980s	Massive seagrass die-off
Maquoit Bay, ME, USA	Trawling	1990s	10% (53 ha) eelgrass loss in 8 yrs.
Puerto Morelos, Mexico	Hurricane	early 1990s	Decreased growth
Hervey Bay, Australia	Cyclone	1990s	1000 km^2 loss
Banda Aceh, Indonesia	Seismic uplift	2006	Local loss in uplift areas

Documented catastrophic losses of seagrasses, from both natural and human-caused impacts, include some which may be climate-change related (based on data from Short and Wyllie-Echeverria 1996 and Green and Short 2003).

Area	Cause	Time	Extent
Westernport, Australia	Sedimentation	1973-1984	85% reduction
Taurnaga, New Zealand	Sedimentation	1959-1996	90% reduction
Wadden Sea, Netherlands	Pollution/turbidity	1970s-1980s	100% loss
Tampa Bay, FL, USA	Nutrient loading/water quality	1950-1963	50% loss bay wide
Indian River Lagoon, FL, USA	Nutrient loading/water quality	1980s	30% reduction
Cockburn Sound, Australia	Nutrient loading/pollution	1970s	>66% loss
French Mediterranean	Pollution/water quality	1970s	40% decline
Lake Grevelingen, Netherlands	Nutrient loading	1970s-1980s	34 km^2 loss
Baltic Sea, Denmark	Water quality	1901 - 1994	75% loss

4.1 EFFECTIVE MANAGEMENT

Effective management is the heart of any conservation strategy aimed towards improving seagrass resilience. This is because seagrasses that are healthy will be better able to adapt to global changes. Managing water quality and maintaining light availability are critical approaches that support seagrass resilience. Managers can reduce land-based pollution by improving land-use practices to decrease nutrient and sediment run-off, reducing or eliminating the use of fertilisers and persistent pesticides and increasing filtration of effluent to improve water quality. Coastal buffer zones may be important for limiting soil, nutrient and pollutant run-offs. Zones of uncultivated soils along rivers and streams combined with undisturbed wetlands can limit the impacts of nutrient and sediment run-off, and protecting these zones through legislation is a key management strategy (Borum et al. 2004).

To manage water quality effectively, managers must link their marine protected areas into the governance systems of adjacent areas, as well as controlling the pollution sources within their own boundaries.

Controlling activities that physically damage seagrass meadows is an important management strategy. For example, building harbours and dredging may adversely affect seagrasses by causing direct physical disturbance. Aquaculture of fish and shellfish can also damage seagrass beds. Such activities can lead to shading and eutrophication from loading of nutrients and organic matter. The building of coastal aquaculture ponds and fish pens in seagrass habitat can cause physical and pollution damage to seagrass meadows. Additionally, physical damage may be caused by boats, moorings, anchors and destructive fishing practices such as bottom

trawling (Marbà et al. 2006) – thus these activities should be regulated in and adjacent to seagrass beds.

Climate change is likely to cause increases in flooding and erosion, so efforts to stabilise vulnerable land areas and strategies that trap sediments and nutrients in the coastal zone before they enter the marine environment will become even more important as climate change impacts intensify (Johnson and Marshall 2007). For example, special fill materials and retention ponds can be used to prevent silt from being washed into the ocean, along with monitoring of turbidity and seagrass health. In Townsville, Australia, this approach was used successfully to prevent coastal development from damaging seagrasses (Coles et al. 2004).

4.2   Mapping

To date, large areas containing seagrasses remain unknown; knowledge gaps exist for many parts of the world, including Southeast Asia, the east coast of South America and the west coast of Africa (Green and Short 2003, Short et al. 2007). In addition, those seagrass areas that are known have seldom been quantified in terms of species diversity, biomass, sediment composition, water quality etc. Local assessment of seagrass distribution followed by monitoring that assesses seagrass health is recommended (www.SeagrassNet.org).

Several techniques for mapping have been devised (Kirkman 1996, Kelly et al. 2001, McKenzie, L.J., Finkbeiner, M.A. and Kirkman, H., Chapter 5 in Short and Coles, eds., Global Seagrass Research Methods). Satellite-based mapping has potential (Ferwerda et al. 2007), although all remote sensing methods have limitations regarding the detection of the seagrass meadows' deep edges (sometimes to depths of 90 m) as well as distinguishing between seagrasses, other marine plants and corals. Inexpensive low-resolution satellite images have been used successfully to map shallow

seagrass beds (Gullström et al. 2006). It should be remembered that extensive ground-truthing is necessary for verifying all remote mapping data (Duarte and Kirkman 2001).

Satellite image of Chwaka Bay, Zanzibar, Tanzania. Source unknown.

4.3   Monitoring

Seagrasses are good indicators of coastal ecosystem changes because their losses signal deteriorating ecological conditions (e.g. water quality, Orth et al. 2006a). Therefore, they are one of five sensitive indicators of pollution in the US National Estuarine Eutrophication Assessment (Bricker et al. 2003). Monitoring of seagrasses also provides valuable information on broader ecosystem health, in addition to seagrass health.

Seagrass monitoring programmes are a relatively recent development. The first programmes were initiated in Australia, the U.S. and France in the early 1980s. Currently, over 40 countries have seagrass monitoring programmes (Orth et al. 2006a). Over the last two decades, multinational projects have developed that include seagrass monitoring components. These include the Cooperative Monitoring in the Baltic Marine Environment, The Caribbean Coastal Marine Productivity Program,

the Mediterranean Posidonia Monitoring Network, the Australasian Seagrass-Watch and the global SeagrassNet.

Monitoring programmes can be implemented at various scales, depending on needs (e.g. Kirkman 1996). For example, line transects can be used to measure the distribution of seagrass beds and can be useful for measuring seagrass declines, but are time consuming so they generally provide limited areal coverage. Remote sensing technologies (e.g. satellite imaging, airborne remote photography, side scan sonar applications), although sometimes expensive, can highlight changes across entire seagrass meadows and provide broad areal coverage.

Monitoring programmes differ in scope and detail, but should consist of regular (e.g. seasonal) measurements of both biotic and abiotic factors of the meadows to quantify health and status as well as trends. Most monitoring programmes assess seagrass cover, biomass and density. More detailed monitoring can also include seagrass growth rates, recruitment and mortality rates, chemical and isotopic composition, shoot length, epiphyte load and genetic diversity, which provide information about status, susceptibility and change within a seagrass community (Borum et al. 2004). Monitoring of seagrass indicators can be complemented by habitat quality indicators (e.g. water quality, light, climatic variables and biological interactions with other organisms) that can provide information on the seagrass status and its change, and thus be the basis for conservation strategies.

Monitoring programmes that address shoot density and cover along transects and in permanent quadrats provide cost-effective locally-based efforts that can detect change quickly (Short et al. 2006). A good complement for assessing larger-scale disturbances is remote sensing for detecting seagrass expansions or retentions (Kendrick et al. 1999, McKenzie, L.J., Finkbeiner, M.A. and

Kirkman, H., Chapter 5 in Short and Coles, eds., Global Seagrass Research Methods). To identify large-scale status and trends, monitoring networks must be coordinated at the local, regional and global scales (Duarte 2002), and quantitative analysis of seagrass trajectories and vulnerability assessments need to be developed to provide for global policies and conservation strategies (Orth et al. 2006a). Improvements in remote sensing techniques hold promise for improved mapping of seagrasses worldwide (Larkum et al. 2006). Models that incorporate the landscape scale of seagrass dynamics and are linked to watershed runoff models are useful for demonstrating the impacts of watersheds on seagrass beds.

It is vital to determine if management actions have been successful in achieving their biological, social and economic objectives. Managers should strive to achieve a balance that maintains seagrass health and at the same time ensures sustainable livelihoods for coastal populations. To ensure long-term effectiveness, managers therefore should develop strategies that incorporate local priorities and needs, and monitor, evaluate and adapt management strategies to reduce anthropogenic impacts and to incorporate resilience to immediate global changes.

4.4 PROTECT REFUGIA

Managers must protect seagrass communities that have demonstrated resilience to climate stressors and/or are naturally positioned to survive global threats (see Fact Box 9). Large seagrass meadows that have persisted through time should accordingly be identified and would be important sites to protect. Also, seagrasses producing a healthy supply of seeds/propagules should be protected for seagrass sustainability. These valuable refuge areas must be protected to supply sources of seeds to repopulate following disturbances (Nystrom and Folke 2001). Several adjacent areas, containing the same species, should be protected since the gene flow between different seagrass populations

Fact Box 9: What Characterises Seagrass Areas that are Well Positioned to Survive Future Stresses?

The following conditions are the primary indicators of seagrass health. Therefore, areas where these conditions are likely to be maintained have good prospects for future seagrass survival.

High water quality: Sufficient light is one of the most important factors for maintaining healthy seagrass meadows. For this, the water must not be allowed to become too turbid (by suspended inorganic materials and/or plankton). While water quality measurements have been described specifically for seagrass environments (Granger and Iizumi 2001), a good rule of thumb is that the irradiance at the seagrass leaves should be higher than 10% of the surface irradiance (Duarte 1991). Light measurements are straightforward (e.g. Carruthers, Longstaff, Dennison, Abal and Aioi 2001, Chapter 19 in Short and Coles, eds., Global Seagrass Research Methods) and several submersible light sensors are commercially available. Other causes of decreasing irradiances could be coloured dissolved substances such as humic acids derived from e.g. mangrove forests. Eutrophication is another factor that decreases water quality and, thus, light. This is because of increased growth of algae in the water column (phytoplankton, causing turbidity) or as epiphytes on the leaves (causing shading).

Seagrass resilience based on high water quality can be assured for seagrass meadows that are 1) not in the vicinity of rivers that could experience major flooding, thus carrying high loads of sediments and 2) away from sites of potential eutrophication. Examples of such potentially resilient areas are therefore shallow offshore meadows and, if near-shore, either undeveloped areas or, if near agricultural lands or urban areas, those that have effective restrictions on land run-off or wastewater treatment.

Favourable water movement: Water movement is important for the supply of nutrients and inorganic carbon to the photosynthesising seagrass leaves. On the other hand, too high water movement may break or uproot the plants. Therefore, it has been estimated that "intermediate current velocities (possibly between 5 and 100 cm s-1) are [enough] to support the growth and distribution of healthy seagrass beds" (Koch 2001). Since exact water flow is hard to measure, areas with continuous visible water movements that do not disrupt the plants or displace the sediment can be considered as good for seagrass growth.

Seagrass resilience based on favourable water movement can be assured for seagrass meadows that are not located in areas facing the threat of stagnancy (i.e. potentially vulnerable areas include lagoons or bays where water movement is restricted and can become cut off due to e.g. construction), nor shallow regions of coastal waters that may face high wave energies (e.g. by the deterioration of protecting reefs). It has been suggested that "the minimum depth of distribution of submerged aquatic vegetation... should be by the mean low water (tide) plus the wave mixing depth" (the latter equalling half a wavelength, Koch 2001).

Good sediment conditions: It is important to maintain an undisturbed root environment for sustaining healthy seagrass growth. The organic load within the sediment must not be too high (<5% may be a fair guideline, Koch 2001), since this may cause both excessive hypoxia (because of a high bacterial O_2 demand) and the danger of sulphide formation. Mechanical perturbations of sediments can also disturb seagrass meadows. These may range from subsistence digging for clams in tropical systems to heavy boating and fishing activities (especially bottom trawling), all of which may uproot seagrasses.

Seagrass resilience based on favourable sediment conditions can be assured for seagrass meadows that are not in the vicinity of organic loading (organic inputs by eutrophication or effluents with high organic contents) or mechanical uprooting (e.g. in no-anchor zones). As for water quality and movement, such conditions can be found in sites away from present and prospective anthropogenic disturbances.

Genetic variability and connectivity: Genetic variability between plants has been proven to be important for seagrass resilience to temperature stress (e.g. Ehlers et al. 2008), but analyses of such variability requires advanced laboratory techniques. On the other hand, it is possible to preserve the documented relatively higher genetic diversity of unstressed areas by allowing for genetic exchanges between meadows. Such gene flows are dependent on current patterns and are severely restricted by distance (as for *Posidonia oceanica*, Procaccini et al. 2001, and for *Zostera marina* where the gene flow is low even at a distance of only 30 km between meadows, Alberte et al. 1994). Resilience can thus be strengthened in seagrass areas with connectivity to one another. Concerning the different vulnerabilities of different species to anthropogenic disturbances, data is presently too scarce to make any recommendations on which particular species is more resilient to environmental changes than the other. Therefore, it seems presently logical to recommend that meadows of high species diversity are those that should be protected.

Effective management: Seagrass meadows within, or adjacent to, coastlines with effective management controlling potential threats (e.g. where run-off of sediments and pollutants are regulated) have a high potential of survival for the future. These include areas with an implemented Integrated Coastal Management Plan or Protected Area Management Plan.

is greatly enhanced by proximity between them (Alberte et al. 1994). Finally, seagrasses that are essential to the livelihoods of local communities should be protected. As described above, many communities rely on seagrass beds as a source of both protein and income (through the animals that thrive there), as well as protectors of their coastal environments (through maintaining clear waters and dampening the effects of wave energy and currents).

4.5 REDUCE THE RISK

To effectively reduce the risk of losing seagrasses by climate change impacts and other anthropogenic disturbances, managers should identify and

Pentaceraster sp. *seastar in* Enhalus acoroides *meadow, inner near-shore, Tanga, Tanzania.*
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protect a wide range of seagrass habitat types that are geographically widespread so as to increase the likelihood of one habitat type surviving a major catastrophic event and, thus, providing a source of seeds and propagules to help damaged seagrass communities recover. Seagrass habitats that are unique or are of particular ecological significance (e.g. areas of high species diversity or areas that provide nurseries for species of special interest) should be included in protected areas. A range of seagrass habitats should be protected that grow in varying environmental conditions such as salinity and tidal fluctuations. It has been suggested that 20-30% of each habitat type should be included in marine protected areas (MPA) networks, based on guidelines developed in temperate and tropical systems (Bohnsack et al. 2000, Day et al. 2002, Airame et al. 2003, Fernandes et al. 2005). Wherever possible, multiple samples of each habitat type should be included in MPA networks (Salm et al. 2006). Protecting replicates of each habitat type in multiple areas reduces the risk that they will all be affected by the same disturbance.

Maintaining biodiversity can enhance resilience if sufficient functional redundancy exists to compensate for species/habitat loss (Bellwood et al. 2004); functional redundancy refers to different species that perform the same functional role in an ecosystem. Maintaining biological diversity is a key strategy to support resilience because it allows more diverse responses to climate change impacts which can provide the basis for adaptation (Johnson and Marshall 2007). Biological diversity includes species diversity, genetic diversity, diversity of species within functional groups, trophic diversity and complexity and diversity of habitats. For example, in seagrass meadows, some species of seagrasses may be genetically more tolerant to thermal stress (e.g. possibly *Enhalus acoroides*, Bridges and McMillian 1986), thus more likely to survive as sea temperatures rise, and such seagrass areas should therefore be protected.

4.6 CONNECTIVITY

Areas where seagrass beds are proven as beneficial to adjacent ecosystems like coral reefs and mangroves should definitely be granted protection. Mangroves, reefs and seagrasses often have a synergistic relationship, based on connectivity, which exerts a stabilising effect on the environment. Seagrasses and mangroves stabilise sediments, slow water movements and trap heavy metals and nutrient rich run-off, thus improving the water quality for corals and fish communities. Seagrasses and mangroves filter freshwater discharges from land, maintaining necessary water clarity for coral reef growth. Coral reefs, in turn, buffer ocean currents and waves to create a suitable environment for seagrasses and mangroves. Mangroves also enhance the biomass of coral reef fish species. It has been shown that seagrass meadows are important intermediate nursery habitats between mangroves and reefs that increase young fish survival (Mumby et al. 2004, Unsworth et al. 2008). Protected area managers

Seagrass, Enhalus acoroides*, with sea anemone and clown fish, Indonesia.*
Copyright: Len McKenzie/SeagrassNet

should secure pathways of connectivity between mangroves, seagrass beds, and coral reefs to enhance resilience (Mumby et al. 2004). Specific steps that can be taken include avoiding the dredging of channels that could alter current patterns or the placement of sewage and storm drain outfalls that could pose either a physical barrier to connectivity or interfere with inshore water movements.

4.7 RESTORATION

Restoration of seagrass beds may be a viable strategy to aid in recovery following disturbances, although it is costly and its success is variable (Short et al 2002b, Orth et al. 2006a). Restoration can either involve improving environmental conditions (e.g. water quality) to encourage natural regeneration or can involve seeding or the transplanting of seedlings or mature plants from donor beds. However, worldwide, only 30% of transplantation and restoration programmes have been successful (Fonseca et al. 1998, Green and Short 2003). Therefore, all restoration programmes should be preceded by careful considerations regarding their feasibility and prospect of success.

Key restoration planning guidelines include:

1. identification of project goals regarding seagrass coverage, species composition and ecological function of restored seagrass beds;

2. coordination of permitting processes to reduce delays in the review and approval process;

3. preservation of genetic diversity (choosing transplant stock from a variety of widely-distributed seagrass beds); and

4. survey and site selection to ensure that existing environmental conditions favour seagrass restoration (Fonseca et al. 1998, Short and Burdick 2005).

Restored Zostera *marina bed from the air, New Hampshire, USA.*
Copyright: Fred Short, University of New Hampshire

Site selection that favours seagrass growth is important (see Fact Box 9, see also Short et al. 2002a and Short and Burdick 2005 for quantitative site selection models). While collecting planting stocks (mature shoots or seeds), care must be taken to minimise damage of the donor meadows. Transplantation is labour intensive because it requires the painstaking harvest of shoots followed by hand or frame transplanting, limiting it applicability for large areas.

A number of seagrass planting methods have been developed (Davis and Short 1997, Harwell and Orth 1999, Orth et al. 1999, Granger et al. 2000, Short et al. 2002b, Paling et al 2001). Restoration objectives, local conditions, seagrass species, and project budgets will determine which planting approach is most appropriate for a given site. Once transplantation has occurred, the sites should be monitored to determine survival rates, shoot density and areal coverage of the transplants. Short-term costs of planting projects range between $25,000 and $50,000 per hectare, while long-term costs over the lifetime of a project may be $80,000 per hectare (Fonseca et al. 1998).

Restoration strategies may help seagrasses to cope with climate change and other anthropogenic impacts and introducing founder populations can speed up ecosystem recovery following a disturbance (Orth et al. 2006b). For example, *Halodule wrightii* is a pioneering species and has been planted as a habitat stabiliser prior to transplanting *Thalassia testudinum* and other seagrasses in restoration efforts (Durako et al. 1992, Fonseca et al. 1998).

Sampling an intertidal seagrass meadow in Ifaty, Madagascar.
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4.8 RAISING AWARENESS – COMMUNICATION/EDUCATION

Creating public awareness of the ecological and social values of seagrasses (see section 2) is essential in building support for seagrass conservation. Governments, academia and non-governmental organisations will then allow for the implementation of available technologies to protect and restore seagrasses and develop ways to improve management, thus producing resilience to climate change in seagrass conservation strategies.

Engaging local communities and stakeholders is essential in any conservation strategy. Volunteer monitoring programmes can be effective in increasing public awareness of the value of seagrass meadows and the threats to their survival. Community monitoring programmes, such as Seagrass-Watch, successfully promote stewardship, reinforce the value of seagrass habitats and collect information about the condition of seagrasses. These and other monitoring programmes (e.g. SeagrassNet) can provide early warnings of important changes within seagrass meadows.

Public education programmes should identify actions that individuals can take to reduce stresses on seagrasses. For example, individuals can help reduce threats to water quality by preventing pollutants (e.g. fertilizers, paint, gasoline, solvents and garden chemicals) from entering storm-water drains. To reduce sediment and nutrient run-off into waterways, individuals can maintain vegetation on riverbanks and adjacent to estuaries, create retention ponds or ditches to reduce high-discharge flows or plant a buffer strip of plants in these areas. Boaters can avoid anchoring and running their propellers through seagrass beds (Turner and Schwarz 2006). The greatest contribution that people can make to mitigate the impacts of climate change on seagrasses is to reduce their overall footprint on earth by driving less and using more energy efficient cars (reducing N and CO_2 emissions), lobbying for better waste disposal practices, avoiding direct run-off of nutrients from animal wastes and farming and gardening practices as well as reducing clear-cutting and deforestation.

5   Tools and Web Resources

A variety of tools exist to help managers in the mapping, monitoring and managing of seagrass habitats. For general seagrass textbooks, see Fact Box 1.

COASTAL REMOTE SENSING TOOLKIT (2006)

The Coastal Remote Sensing Toolkit developed at the University of Queensland, Australia, helps managers, scientists and technicians in coastal environments understand how remote sensing imagery can be used to map and monitor changes in indicators of coastal ecosystem health including seagrasses, coral reefs, and mangroves.
See http://www.gpa.uq.edu.au/CRSSIS/tools/rstoolkit/index.html

FLORIDA SEAGRASS MANAGERS TOOLKIT (2003)

The Florida Seagrass Managers Toolkit was developed for resource managers, decision makers and the public. The objectives of the toolkit are to help users identify seagrass management issues and provide an introduction to possible management strategies. The toolkit includes an introduction that describes the ecological importance of Florida's seagrass habitats and the need for effective management. It also includes information on mapping and monitoring tools and protection and restoration tools.
See http://research.myfwc.com/features/view_article.asp?id=23202

DOCK DESIGN WITH THE ENVIRONMENT IN MIND: MINIMIZING DOCK IMPACTS TO EELGRASS HABITAT (1998)

This interactive CD-ROM, by D.M. Burdick and F.T. Short, is an interactive programme that provides education and conservation information on eelgrass and explores the impacts of dock and pier construction on eelgrass meadows.
Produced by UNH Media Services©, UNH and available at UNH SeaGrant: steve.adams@unh.edu

A MANUAL FOR COMMUNITY-BASED EELGRASS RESTORATION (2002)

by F.T. Short, C.A. Short and C. Burdick-Whitney, is an information package with complete methods for seagrass restoration by community volunteer groups. The CD contains, a manual for restoration using TERFS™, an informational brochure, and instructional Power Point presentation. Sponsored by NOAA Restoration Center, University of New Hampshire, Durham, NH.
See http://marine.unh.edu/jel/faculty/fred2/fredshort.htm

EELGRASS RESTORATION AND SITE SELECTION MODEL (2005)

A CD by F.T. Short and D.M. Burdick that utilises readily available local data to determine prioritized locations for the restoration of eelgrass beds. When coupled with a GIS program, maps are produced that identify sites with the best potential for eelgrass restoration.
For a copy, email: seagrass.net@unh.edu

Seagrass-Watch (1998)

Seagrass-Watch is a community-based seagrass monitoring programme that was developed in Australia in 1998. The project aims to 1. educate the public on the importance of seagrass resources, 2. raise awareness of coastal management issues, 3. build the capacity of local stakeholders in the use of standardised scientific methodologies, 4) conduct long-term monitoring of seagrass and coastal habitat condition, and 5) support the resilience of seagrass ecosystems through conservation measures. See http://www.seagrasswatch.org/about.html

SeagrassNet (2001)

SeagrassNet is a global monitoring programme started in 2001 that assesses the status of seagrass resources including human impacts and global climate change. The goal of the programme is to preserve seagrass ecosystems by increasing scientific knowledge and public awareness, and to provide a "global report card" of seagrass health. SeagrassNet teams are trained in the monitoring method and submit data via the internet to an online database quarterly. A detailed methods manual in English or Spanish is downloadable with regional supplements. See http://www.seagrassnet.org

World Seagrass Atlas On-line Database (2003)

Based on information collected for the World Atlas of Seagrasses (Green and Short 2003), the On-line Database is a compilation of seagrass species distribution information that is available via an Interactive Map Service at the website below. Global seagrass data includes both map polygons and point data. New seagrass distribution information can be submitted to seagrass.net@unh.edu See http://www.unep-wcmc.org/marine/seagrassatlas/index.htm

6   Summary and Conclusions

Thalassia hemprichii *with* Enhalus acoroides *in the background, Kosrae, Federated States of Micronesia.*
Copyright: Peter Lamb, SeagrassNet

Seagrasses are submerged marine flowering plants forming extensive meadows in many shallow coastal waters worldwide. The leafy shoots of these highly productive plants provide food and shelter for many animals (including commercially important species, e.g. prawns), and their roots and rhizomes are important for oxygenating and stabilising bottom sediments and preventing erosion. The monetary value of seagrass meadows has been estimated at up to $19,000 per hectare per year, thus being one of the highest valued ecosystems on earth.

Many seagrass habitats have already been severely impacted by human activities, and may be additionally affected by global climate change. Seagrass meadows are especially vulnerable to:

SEDIMENT LOADING AND DISTURBANCES

Any perturbation of sediments may have negative effects on seagrass meadows. Additions of sediments caused by storms, flooding, coastal soil erosion, dredging near seagrass meadows or coastal construction may smother the plants irreversibly or create high concentrations of suspended sediments that reduce the light reaching the seagrasses. Also removal of sediments within seagrass meadows, often caused by the same factors, may in other areas uproot seagrasses.

EUTROPHICATION

The addition of excess nutrients to coastal areas may cause excessive growth of opportunistic, fast-growing, algae (seaweeds, epiphytic algae and/or

phytoplankton). These algae will then shade the seagrass leaves, possibly causing their death (especially if they already grow under critically low light conditions). Another effect of eutrophication is the increased loading of organic materials (e.g. dead algae) to the sediment, which increases its O_2 demand and may cause excessive hypoxia, thus killing the seagrass roots.

LIGHT REDUCTIONS

In addition to light reductions by sedimentation and eutrophication, climate change may also reduce light by shifting weather patterns to cause increased cloudiness or by increased water depth caused by sea level rise.

TEMPERATURE INCREASES

One of the most widely mentioned global changes is increased temperature. Since seagrasses feature various tolerances to temperature, it follows that certain species may decline drastically (e.g. the temperate *Zostera marina* growing in monospecific meadows) while others may become replaced by more temperature-tolerant ones (e.g. in temperate-tropical interface areas).

Global change impacts include effects of increasing seawater CO_2 levels and decreasing pH (ocean acidification). While this could affect seagrass photosynthesis and growth, too little data is available today in order to predict the effects of CO_2 and pH on seagrass meadows. The main effect of global change will be synergistic in that already stressed seagrass systems will be exposed to additional stressors that push them over their limit of existence, resulting in widespread seagrass losses.

Some seagrasses acclimate to changing environmental conditions better than others. Intra-meadow genetic diversity has been shown to be a key factor supporting the resilience of *Zostera marina*, and efforts should be devoted to investigating such mechanisms in other key seagrasses.

Six seagrass species can be found in this photo taken in Palau: Enhalus acoroides, Cymodocea rotundata, Cymodocea serrulata, Thalassia hemprichii, Syringodium isoetifolium, and Halodule uninervis.
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Effective management of seagrass meadows is essential in order to maintain these valuable ecosystems and their important functions. Controlling human impacts will help maintain healthy seagrasses that are better able to resist or recover from climate change impacts. In addition to effective management, the following steps should be taken by managers to support the resilience of seagrass systems:

MAPPING

Baseline mapping should be done to assess seagrass resources, plan management strategies and monitor changes.

MONITORING

Regular assessments are important in order to identify disturbances to seagrass habitats and to determine management efforts. These assessments should include seagrass abundance (cover, density and/or biomass), habitat extent and spe-

Enhalus acoroides (large) and Thalassia hemprichii (small) in Kosrae, FSM.
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cies composition (in mixed meadows). Monitoring of water quality (including light penetration) and sediment composition could be of importance as early warnings of disturbances. Likewise, changes in other biotic factors (e.g. fauna and other plants) may indicate disturbances in the meadows or in the habitats they are connected with.

CONNECTIVITY

It should be established where seagrass meadows are ecologically linked to adjacent habitats (e.g. mangroves or coral reefs). Such linkages should be taken into account when designing protected areas and management plans.

PROTECTION

Refugia should be identified and protected, and should include a broad range of seagrass habitats so as to preserve plants and seeds for later recovery of damaged areas.

RESTORATION

Allow regeneration of critical seagrass areas by eliminating the causes of their decline. If possible,

and if sufficient funds are available, founder populations can be transplanted into areas where seagrasses have been decimated or eliminated (after the impact has been removed).

AWARENESS

Spread awareness about seagrasses and the importance of maintaining healthy seagrass habitats to the general public, environmentalists and policy makers.

Overall, seagrasses are in a vulnerable state. Many meadows are presently declining, and are further threatened by global change scenarios. Effective management, including actions to promote public awareness, can increase the resilience of these important habitats. If protected, healthy seagrass meadows will continue to support the many fish, invertebrates, dugongs, manatees, green turtles, seabirds and *Homo sapiens* living within or near the meadows, as well as the biota of coral reefs and mangrove forests.

Glossary

Abiotic (factors): Non-biological (as opposed to biotic), e.g. salinity, currents, light etc.

Aerobic: Process in which O_2 is involved, e.g. aerobic respiration

Angiosperm: Flowering plant

Anoxic: Without (completely lacking) O_2

Benthic: Connected with, or living near, the sea bottom

Biotic (factors): Belonging to, or caused by, the living organisms (as opposed to abiotic), e.g. grazing

Chloroplast: Cell organelle in which photosynthesis takes place

Climax species: Species which are stable and capable perpetuating themselves.

Clone: Organisms having identical genome

Detritus: Decomposing organic material

Dioecious : Dioecious: Female and male flowers occurring on different plants (as opposed to monoecious)

Greenhouse gasses: Gasses that contribute to the greenhouse effect, i.e. hinder heat radiation from escaping through the atmosphere

Hypoxic: Low in O_2

Infauna: Animals that live within the sediment

Irradiance: The amount of radiation (usually referred to as light)

Lacuna: Air canals (through which gasses can diffuse between different parts of a seagrass plant)

Light: That part of the electromagnetic spectrum that supports vision and photosynthesis; see also irradiance

Light attenuation: The decrease in light (e.g. along a depth gradient)

Macroalga (also called seaweed): Alga that is large enough to be seen with the naked eye (as opposed to microalgae)

Meristem: Growth area of leaves, roots and rhizomes; area of high cell division activity

Microalga: Alga that is so small that it can only be seen using a microscope (as opposed to macroalga)

Monoecious: Both female and male flowers occurring on the same plant (as opposed to dioecious)

Non-photochemical quenching (of photosynthesis): Dissipation of light energy that results in heat

Oligotrophic: Nutrient-poor

Opportunistic species (also called r-strategist): Species that grow and multiply fast when conditions are favourable

Photoinhibition: Decreased photosynthetic rate because of too high irradiance

Photosynthetically active radiation (PAR): That part of the electromagnetic spectrum that supports photosynthesis (400-700 nm)

Phytoplankton: Free floating plants that drift with the currents (usually of microscopic size)

Plankton: Organism that drifts with the currents. See also phytoplankton and zooplankton

Pioneering species: Species that establishes itself in a barren environment

Propagule: Part of a plant that can detach and then form a new rooted plant

Rhizome: Horizontal underground "stem" that connects the various shoots of a clone

Rhizosphere: The area surrounding roots and rhizomes

Seaweed: see macroalga

Trophic (level): Level in the food chain (e.g. primary producer, herbivore, carnivore)

Vascular: Having transport systems (vascular bundle) for water upwards (xylem) and photosynthates to non-photosynthetic parts of the plant (phloem)

Wrack: Detached seagrass leaves that collect together and drift on the water surface or are washed up on the shoreline

Zooplankton: Animals that drift with the currents (usually of microscopic size)

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Notes

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