MANAGING SEAGRASSES FOR RESILIENCE TO CLIMATE CHANGE

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1. INTRODUCTION

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, 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.

There is growing evidence that seagrasses are experiencing declines globally due to anthropogenic threats (Short and Wyllie-Echeverria 1996, Hemminga and Duarte 2000, Duarte 2002). Runoff of nutrients and sediments that affect water quality is the greatest anthropogenic threat to seagrasses, 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

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 C. 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

Fact Box 2: The Origin of Seagrasses

pollination and seed production. Because seagrasses evolved from three independent ancient lineages, they show morphological differences in structure; 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 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.

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 them 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 3e) 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 divert 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 repr prevents erosion (Hemminga and Duarte 2000). Seagrasses grow well 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 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 1998).

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 photosyn 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 reef flats by villagers, nursery resources for commercially important finfish and shellfish species, and habitats for commercial and recreational bivalve fisheries.

2d. 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 km^2 (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 prohibitive.

The distribution of seagrass has been defined into six global bioregions (Short et al. 2007). Seagrasses of the tropics are high in species diversity and are found in the Tropical Indo-Pacific and the Tropical Atlantic bioregions. 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 is a region of low seagrass diversity, where the dominant species is *Zostera marina*. The Temperate North Pacific region is also dominated by *Zostera marina*, but is a region of higher seagrass diversity with several *Zostera* species, as well as several *Phyllospadix* species in the surf zone. The Southern Ocean's bioregion is a circum-global area including the temperate coastlines of Australia, Africa and South America, where extensive meadows of both 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 species of the same seagrass 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.

Changes in seagrass distribution patterns may happen quickly, as seagrasses respond to local environmental changes at the edges of the bioregions, where we now find mixes of tropical and temperate species. It is these sites where shifts will most likely occur rapidly in response to global climate change. However, the detection of this change is complicated because many of these areas are sites of more direct and immediate human impacts than those causing global climate change, where seagrasses are already stressed by reduced light and extreme temperature or are areas under siege by invasive species of algae.

2e. Growth and Productivity

Most seagrass stands begin as seedlings (although some may begin as propagules of detached shoots), 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 were previously measured as leaf growth (Zieman1974, Dennison 1990), but quantitative leaf measurements seldom reflect the growth of the whole plant since neither the proportions of growth of the underground rhizomes and roots (Short and Duarte 2001), nor the stage of leaf maturation (Gaeckle and Short 2002) are generally known. Seagrass growth methodology has in some cases been refined to express whole plant growth by incorporating the growth of both above- and below-ground vegetative expansion (Short and Duarte 2001), thereby initiating more realistic productivity metrics. Still lacking is the ability to assess whole plant growth correctly from measures of photosynthesis. Variations ir.6(y)-a0.008 Tw[eox(a0.0t a8iy[(ow)-462.c i)u TD-51ns iearaeow0.008 Twf0 TD-0.h new

to depths less than 70 m (Short et al. 2007). However, in many parts of the world, particularly near large river discharges or

2f. Benefits of Seagrasses

Seagrasses have had many traditional uses (cf. Terrados et al. 2004). Among them, 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 used as a food source.

While only a few larger animals possess the ability to actually digest seagrass leaves (dugongs, turtles, geese, brants, and some herbivorous fish), seagrass 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 at night to feed on the rich food sources within the seagrass meadows. Many small subsistence fishing practices, such as those practiced 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 seagrass 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 sediment sink due to their slow rate of decomposition. For example, the rhizomes of *Posidonia oceanica* may in the Mediterranean form massive structures 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 they store 12% of it (Duarte and Cebrian 1996).

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eutrophication (Burdick et al. 1993, Harwell and Orth, 2002), fluctuating salinity (Grillas et al. 2000) and global warming (Harvell et al. 2002), no such links have been identified.

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).

3a. Anthropogenic Non-Climate Related Impacts

The two largest human impacts to seagrasses worldwide are sediment loading and eutrophication. In the tropics, sediment loading and suspended sediments, causing turbidity, may have the greatest impact (Duarte et al. 2008). Eutrophication is a more common problem 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). 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 declined seagrass survival. All these discharges into tropical areas have major impacts on water clarity, thus reducing the light available to seagrasses.

Nutrient inputs into shallow marine systems may yield different results with regard to seagrass production. 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.

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 (Marba et al. 2006) and, thus, in the extent of the meadows. 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.

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3b. 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 consequences also 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, although about 30% of all atmospheric CO_2 resulting from 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 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 (although experimental evidence for this hitherto 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* photosynthesis in such dense, or isolated, 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 (Sheppard and Rioja-Nieto 2005). Temperature stress on seagrasses will result in distribution shifts, changes in patterns of sexual reproduction, altered

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*

(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 as a result of global change (strictly according to Darwin), making it possible for the meadow to remain functioning (albeit with an altered species composition). Such a reasoning may apply to other climate impacts as well.

Fact Box 7: How to Identify Threats to Seagrasses

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). Various abiotic aspects of the water quality should be monitored too (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?

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. Management organizations can thus reduce their own climate footprint in support of global mitigation efforts (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, ther

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 spreading them out.

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, ensure 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: Major Seagrass Losses

Documented catastrophic losses of seagrasses include natural and human-made sudden impacts including some which may be climate change related (based on data from Short and Wyllie-Echeveria 1996 and Green and Short 2003).

Area	Cause	Time	Extent
North Atlantic	Wasting disease	1930s	90% eelgrass in 5 years.
Prince William Sound, AK	Earthquake	1960s	
Chesapeake Bay	Water quality	1970s	
Great Bay, NH	Wasting disease	1980s	80% eelgrass loss in 2 years
Waquoit Bay, MA	Nitrogen loading	1980s	85% eelgrass loss in 6 years
Florida Bay	Unknown	1990s	
Maquoit Bay, ME	Trawling	1990s	10% (53 ha) eelgrass loss in 8 yrs.

Tampa Bay, FL	Nutrient loading/water quality	1980s
Indian River Lagoon, FL	Nutrient loading/water quality	1980s
Cockburn Sound, Australia	Nutrient loading/pollution	1970s
French Mediterranean	Pollution/(water quality)	1970s
Lake Grevelingen, Netherlands	Nutrient loading	1970s-1980s
Baltic Sea, Denmark	Water quality	1901 - 1994

4a. 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 beds 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 beds. Additionally, physical damage may be caused by boat propellers, 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).

4b. Mapping

To date, large areas containing seagrasses probably 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 et al. 2001). Satellite-based mapping has potential (Ferwerda et al. 2007), although all remote sensing methods have limitations regarding the detection of the seagrass beds' deep edges (sometimes to depths of 90 m) as well as distinguishing between seagrasses, other marine plants and corals. Also, inexpensive low-resolution satellite images have be used successfully to map 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).

4c. Monitoring

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

Seagrass monitoring programmesare 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, 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 bala 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 ty could alter current patterns or the placement of sewage and storm

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 **pioneering species** and have been planted as a habitat stabiliser prior to transplanting *Thalassia testuninum* and other seagrasses in restoration efforts (Durako et al., 1992; Fonseca et al., 1998).

4g. 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 hopefully 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 data 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

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.

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 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. Since data on the vulnerability of different species to anthropogenic disturbances is presently too scarce to make any recommendations on which particular species is more resilient to environmental changes than the other, it seems at this stage 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.

6. SUMMARY AND CONCLUSIONS

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 aer heri3 at e per .4(oots oat ea)9.thus55 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 rises.

* 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

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 of or within the meadows, as well as the biota of coral reefs and mangrove forests.

7. 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

Clone: Organisms having identical genome

Detritus: Decomposing organic material

Dioecious: Either female or male flowers occurring on the same plant

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 channel (through which gasses can be transported between different parts of a seagrass plant)

Light: That part of the electromagnetic spectrum that causes 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 see 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

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 causes photosynthesis (400-700 nm)

Phytoplankton: plants that drift with the currents (usually small)

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

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 surrounding of the roots

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)Lacuna: Air canal for the transport of O_2 from the leaves to the roots and possibly CO_2 from the roots to the leaves

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 small)

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