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Review

Environmental impacts of dredging on seagrasses: A review

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Abstract

Main potential impacts on seagrasses from dredging and sand mining include physical removal and/or burial of vegetation and effects of increased turbidity and sedimentation. For seagrasses, the critical threshold for turbidity and sedimentation, as well as the duration that seagrasses can survive periods of high turbidity or excessive sedimentation vary greatly among species. Larger, slow-growing climax species with substantial carbohydrate reserves show greater resilience to such events than smaller opportunistic species, but the latter display much faster post-dredging recovery when water quality conditions return to their original state. A review of 45 case studies worldwide, accounting for a total loss of 21,023 ha of seagrass vegetation due to dredging, is indicative of the scale of the impact of dredging on seagrasses. In recent years, tighter control in the form of strict regulations, proper enforcement and monitoring, and mitigating measures together with proper impact assessment and development of new environmental dredging techniques help to prevent or minimize adverse impacts on seagrasses. Costs of such measures are difficult to estimate, but seem negligible in comparison with costs of seagrass restoration programmes, which are typically small-scale in approach and often have limited success. Copying of dredging criteria used in one geographic area to a dredging operation in another may in some cases lead to exaggerated limitations resulting in unnecessary costs and delays in dredging operations, or in other cases could prove damaging to seagrass ecosystems. Meaningful criteria to limit the extent and turbidity of dredging plumes and their effects will always require site-specific evaluations and should take into account the natural variability of local background turbidity.

Keywords: Critical thresholds; Dredging impacts; Mitigation; Review; Seagrasses; Turbidity

1. Introduction

Dredging is required in many ports of the world, to deepen and maintain navigation channels and harbour entrances. Elsewhere, commercial sand mining and extraction of sand and gravel from borrowing areas is meeting an ever-increasing demand for sand for construction and land reclamation. Excavation, transportation and disposal of soft-bottom material may, however, lead to various adverse impacts on the marine environment (USACE, 1983; ABP Research, 1999). Such impacts can be especially significant when dredging or disposal is done in the vicinity of sensitive marine environments, such as coral reefs and seagrass beds.

Seagrass beds, covering about 0.1–0.2% of the global ocean floor, are highly productive ecosystems which fulfill a key role in the coastal zone (Duarte, 2002). Important ecological and economic functions of seagrass beds have been widely acknowledged, notably their importance to fisheries (Bell and Pollard, 1989; Jackson et al., 2001) and their role in preventing coastal erosion and siltation of coral reefs (Scoffin, 1979; Fonseca and Fisher, 1986; Fonseca, 1989). Conservative estimates of the value of ecosystem services provided by seagrass beds are in the order of 19,000 US\$ ha^{-1} yr^{-1} (Costanza et al., 1997).

Globally, the estimated loss of seagrass from direct and indirect human impacts is updated to be 33,000 km^2 over the last two decades, based on an extrapolation of known losses (Short and Wyllie-Echeverria, 2000) and a new global seagrass area estimate of 177,000 km^2 (Green and Short, 2003). The primary cause of seagrass degradation

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and loss globally is reduction in water clarity, both from increased turbidity and increased nutrient loading (Walker and McComb, 1992; Duarte, 2002; Short, 2003). In many cases, dredging operations have directly or indirectly contributed to loss of seagrass vegetation. For example, combined impacts of increased turbidity and physical removal or burial during dredging, and eutrophication from nutrients in domestic and industrial discharges caused the loss of approximately 81% of the seagrasses in Tampa Bay, Florida (Lewis, 1976; Lewis et al., 1985).

Some seagrass species appear more sensitive than others to increases in turbidity or sedimentation that are commonly associated with dredging operations. Their response to such increases may depend on typical local conditions and vary between seasons. In general, the impact from dredging and sand mining on seagrass ecosystems is complex and far from fully understood, despite various research efforts. Initial investigation by the authors has shown that there is an extensive body of experience to learn from. This experience lies with contractors, in Environmental Impact Assessment (EIA) reports, monitoring data and scientific literature derived from field-based and laboratory studies on potential direct and indirect effects of dredging.

This paper presents a worldwide review of documented cases of dredging and sand mining operations in or near seagrass meadows. The scale of such operations and environmental impacts thereof, as well as restrictions and mitigating measures put into place to minimize these impacts will be discussed. Where appropriate, these findings will be illustrated with case studies. The focus of this review is limited to dredging for the purpose of deepening of ports and navigation channels as well as for extraction and mining of sediments for construction and land reclamation schemes. Other forms of dredging, such as hydraulic clam dredging and cockle fishing, or damage to seagrass beds by boat groundings, propellor scarring and anchoring, were not considered. Information sources for the review included peer-reviewed scientific literature, gray literature in the form of EIA-, consultancy and technical reports, and additional information obtained from the internet and email responses to general requests placed on internet-based research discussion lists.

2. Environmental impacts of dredging

Potential effects of dredging on the marine environment include effects of the dredging process (i.e. the removal of substratum from the seafloor) as well as effects caused by the process of disposal. Dredged material may come into suspension during dredging itself as a result of disturbance of the substratum, but also during transport to the surface, overflow from barges or leakage of pipelines, during transport between dredging and disposal sites, and during disposal of dredged material (Jensen and Mogensen, 2000).

Dredging may affect the physical environment by changing the bathymetry, altering current velocities and wave conditions (Jensen and Mogensen, 2000) which affect the sedimentary regime and may cause erosion under seagrass beds (MacInnis-Ng, 2003).

Dredging and disposal of dredged material can lead to a temporary decrease in water transparency, increased concentrations of suspended matter, and increased rates of sedimentation. In the case of contaminated sediment or sediments with high contents of organic matter, dredging and resuspension may also lead to effects on water quality by the release of contaminants (e.g. Filho et al., 2004), an increase in nutrients concentrations and reduced dissolved oxygen in the water column.

Physical removal of substratum and associated plants and animals from the seabed, and burial due to subsequent deposition of material are the most likely direct effects of dredging and reclamation projects (Newell et al., 1998). New habitats may also be created as a result of the operation, either directly in the dredged area or by introduction of new habitats on the slopes of a reclaimed area (e.g. hard substratum in the form of breakwaters and revetments).

Other direct effects may be caused by enhanced turbidity and sedimentation as a result of dredging and disposal operations. The effect of turbidity on seagrass ecosystems is two-fold. Light attenuation by suspended material affects the amount of light available to the seagrass plants and associated epiphytes, microphytobenthos and macroalgae. Depending on the depth at which these organisms occur, high turbidity can cause a significant reduction in light availability leading to sub-lethal effects or death. High levels of suspended material can lead to reduced vitality or death in benthic fauna associated with the seagrass beds through clogging of their feeding mechanisms (cilia and siphons) and smothering, especially in filter-feeding organisms such as mussels, oysters and other bivalves. To capture both effects of turbidity, critical thresholds for turbidity should therefore ideally be determined in terms of light availability at the bottom (in % of surface irradiance) as well as in concentration of total suspended solids (in mg/l).

Increases in turbidity can also be caused by algal blooms, sewage discharge, bio-fouling of turbidity sensors etc. Turbidity should therefore not only be expressed in terms of a reduction of light availability as the sole measure of water quality affected by dredging works, but preferably be accompanied by investigations of the suspended solid concentrations (Bogers and Gardner, 2004).

Turbidity changes induced by dredging will only result in adverse environmental effects when the turbidity generated is significantly larger than the natural variation of turbidity and sedimentation rates in the area (Stern and Stickle, 1978; Orpin et al., 2004). Such natural variability can sometimes be substantial and may be caused by factors such as storms, wind-induced wave actions, river discharges and other local perturbations. Dredging activities often generate no more increased suspended sediments than commercial shipping operations, bottom fishing or severe storms (Pennekamp et al., 1996).

The degree of adverse environmental impacts caused by dredging and disposal depends on the quantity, frequency and duration of dredging, methodology of dredging and disposal, physical dimensions and water depth of the dredging location, grain-size composition, density and degree of contamination of the dredged material, background water quality (especially suspended matter and turbidity), seasonal variations in weather conditions (especially wind and waves), and proximity/distance of ecologically sensitive or economically important areas or species relative to the location of the dredging or disposal site (Pennekamp et al., 1996). Depending on these factors, there can be considerable spatial and temporal variation in effects. In some cases, adverse impacts of dredging activities are limited to a relatively small area and of relatively short duration. Other (more large-scale) dredging or sand mining operations, which stretch out over several years and cover many square kilometres, can have major adverse environmental impacts (Lewis, 1976).

In summary, main potential impacts from dredging on seagrasses include physical removal or burial of vegetation at the dredging/disposal site, and increased turbidity (light reduction) and increased sedimentation in adjacent seagrass meadows. In addition, temporarily reduced dissolved oxygen concentration, release of nutrients and pollutants from (contaminated) sediments, and hydrographic changes may also occur and have adverse (indirect) effects on the seagrass ecosystem.

3. Critical thresholds of seagrasses for turbidity

Light is one of the key environmental resources imperative for the growth and survival of seagrasses (Hemminga and Duarte, 2000). Water transparency (which determines depth-penetration of photosynthetically active radiation of sunlight) is the primary factor determining the maximum depth at which seagrasses can occur. Reduction in light due to turbidity has been identified as a major cause of loss of seagrasses worldwide (Shepherd et al., 1989; Green and Short, 2003). The amount of light that reaches a seagrass leaf is determined by the natural water colour, concentration of suspended solids, phytoplankton concentration and epiphyte cover of the leaf (Dennison, 1991; Batiuk et al., 2000).

There are various reports of sublethal and lethal effects on seagrass meadows due to prolonged exposure to high turbidity and siltation associated with dredging activities (Caldwell, 1985; Gaby et al., 1986; Onuf, 1994; Gordon et al., 1996; Chesire et al., 2002; Sabol et al., 2005). Indicators of light stress in seagrasses may include decreases in below-ground biomass and carbohydrate contents of rhizomes, tissue nutrient contents, Chl-a contents of leaves and various photosynthetic growth parameters (Coles and McKenzie, 2004).

There is a considerable range of values (2.5–37% of SI) reported in the literature for the minimum light requirements of seagrasses, varying between different seagrass species as well as within a single seagrass species (Table 1). The order of magnitude of this variation is similar between species and within species (Fig. 1). Minimum light requirements of most seagrass species seem to vary between 15% and 25% of SI (means of reported values per species), but for some species (*Cymodocea nodosa*, most *Halophila* spp. and some *Posidonia* spp.) minimum light requirements as low as 3–8% of SI have been reported (Table 1, Fig. 1).

The variation in minimum light requirements reported in literature is in part caused by differences in the methodologies used to derive these values. Methodologies range from physiological studies of photosynthesis/irradiance relationships, field observations of maximum depth of seagrass colonization, and experimental manipulation of light levels during growth studies, to statistical models (Batiuk et al., 2000). Studies and methods further differ in the degree to which attenuation by epiphyte cover of seagrass leaves, natural water colour, seasonal variation, above-/below-ground biomass ratios, environmental factors other than light, and sublethal effects have been taken into account. Mesocosm experiments have clearly shown effects of shading on plant architecture, biomass partitioning, lateral shoot development and flowering intensity in eelgrass (Ochieng et al., 2004).

Whilst minimum light requirements are important, it is an oversimplification to assume that light attenuation alone determines plant response to increased turbidity. Also of importance is the length of time that different species can survive at low light levels. Temporary fluctuations in turbidity may be accommodated by the plant depending on the nature of the species and the period of sub-optimal light (Westphalen et al., 2004). Laboratory experiments have shown that some seagrasses can survive in light intensities below their minimum requirements for periods ranging from a few weeks to several months (Table 2) (Backman and Barilotti, 1976; Bulthuis, 1983; Gordon et al., 1994; Czerny and Dunton, 1995; Longstaff et al., 1999). Widespread seagrass mortality was observed in Chesapeake Bay (USA) following a month-long (seasonal) pulse of increased turbidity (Moore et al., 1997).

The survival period of seagrass below its minimum light requirement is shorter in smaller species with low carbohydrate storage capacity than in larger species (Longstaff et al., 1999; Peralta et al., 2002). Work by Chesire et al. (2002) indicates that *Posidonia sinuosa* is able to survive longer at sub-compensation light levels than *Zostera tasmanica*, which in turn survives slightly longer than *Z. marina*, while *Halophila ovalis* copes with sub-minimal light for the shortest period. Whilst these results used different methodologies and measurements to determine survival, it is clear that species with larger below-ground biomass are better adapted to longer periods of sub-minimal light.

4. Critical thresholds of seagrasses for sedimentation

Several studies have documented deterioration of seagrass meadows by smothering due to excessive

Table 1
Critical threshold of seagrasses for light availability ('minimum light requirements' expressed as % of surface irradiance SI)

Species	Location	% SI	Reference
Amphibolis antarctica	Waterloo Bay, Australia	24,7	Duarte (1991)
Cymodocea nodosa	Malta	7,3	Drew (1978)
Cymodocea nodosa	Ebro Delta, Spain	10,2	Duarte (1991)
Halodule wrightii	Laguna Madre, Texas, USA	5	Dunton and Tomasko (1991)
Halodule wrightii	Alabama, USA	14	Shafer (1999)
Halodule wrightii	Texas, USA	16	Czerny and Dunton (1995)
Halodule wrightii	Texas, USA	16	Onuf (1996)
Halodule wrightii	Florida, USA	17,2	Dennison et al. (1993)
Halodule wrightii	Texas, USA	17,5	Onuf (1991)
Halodule wrightii	Texas, USA	18	Dunton (1994)
Halodule wrightii	Texas, USA	18	Dunton and Tomasko (1994)
Halodule wrightii	Indian River Lagoon, Florida, USA	29,5	Beal and Schmit (2000)
Halodule wrightii	Indian River Lagoon, Florida, USA	30,5	Kenworthy and Fonseca (1996)
Halophila decipiens	Hobe Sound, Florida, USA	2,5	Dennison (1987)
Halophila decipiens	St.Croix, Caribbean	4,4	Williams and Dennison, 1990
Halophila decipiens	Northwest Cuba	8,8	Duarte (1991)
Halophila engelmanni	Northwest Cuba	23,7	Duarte (1991)
Halophila ovalis	Zanzibar, Tanzania	16	Schwarz et al. (2000)
Halophila spp.	Sub tropical seas	5	Dennison et al. (1993)
Halophila stlpulacea	GulfofEilat, Red Sea	3	Beer and Waisel (1982)
Heterozostera tasmanica	Spencer Gulf, Australia	4,4	Duarte (1991)
Heterozostera tasmanica	Victoria, Australia	5	Bulthuis (1983)
Heterozostera tasmanica	Australia	9	Bulthuis and Woelkerling (1983)
Heterozostera tasmanica	Chile	17,4	Duarte (1991)
Heterozostera tasmanica	Waterloo Bay, Australia	20,2	Duarte (1991)
Posidonia angustifolia	Waterloo Bay, Australia	24,7	Duarte (1991)
Posidonia australis	Australia	10	Fitzpatrick and Kirkman (1995)
Posidonia coriacea	Adelaide coast, Australia	8	Westphalen et al. (2004)
Posidonia oceanica	Medas Island, Spain	7,8	Duarte (1991)
Posidonia oceanica	Malta	9,2	Drew (1978)
Posidonia oceanica	Corsica, France	10–16%	Dalla Via et al. (1998), Ruiz and Romero (2003)
Posidonia ostenfeldii	Waterloo Bay, Australia	24,7	Duarte (1991)
Posidonia sinuosa	Australia	20	Gordon et al. (1994)
Posidonia sinuosa	Waterloo Bay, Australia	24,7	Duarte (1991)
Ruppiamaritima	Brazil	8,2	Duarte (1991)
Ruppia maritima	Australian estuary	28	Congdon and McComb (1979)
Ruppia megacarpa	Western Australia	24	Carruthers et al. (1999)
Syringodium filiforme	Florida, USA	17,2	Dennison et al. (1993)
Syringodium filiforme	Florida, USA	18,3	Duarte (1991)
Syringodium filiforme	Northwest Cuba	19,2	Duarte (1991)
Syringodium filiforme	Indian River Lagoon, Florida, USA	30,5	Kenworthy and Fonseca (1996)
Thalassia testudinum	Florida, USA	10	Fourqurean et al. (1999)
Thalassia testudinum	Texas, USA	14	Czermy and Dunton (1995)
Thalassia testudinum	Texas, USA	14	Lee and Dunton (1997)
Thalassia testudinum	Florida, USA	15	Fourqurean and Zieman (1991)
Thalassia testudinum	Florida, USA	15,3	Duarte (1991)
Thalassia testudinum	Gulf of Mexico	20	Iverson and Bittaker (1986)
Thalassia testudinum	Florida Bay, USA	20	Stumpf et al. (1999)
Thalassia testudinum	Tampa Bay, Florida, USA	22,2	Dixon (2000)
Thalassia testudinum	Northwest Cuba	23,5	Duarte (1991)
Thalassia testudinum	Puerto Rico	24,4	Vicente and Rivera (1982)
Zostera capricomi	Moreton Bay, Australia	30	Longstaff et al. (1999)
Zostera capricomi	Moreton Bay, Australia	30	Abal and Dennison (1996)
Zostera marina	New Hampshire, USA	11	Short et al. (1995)
Zostera marina	Japan	18,2	Duarte (1991)
Zostera marina	Woods Hole, USA	18,6	Dennison (1987)
Zostera marina	Roskilde, Denmark	19,4	Borum (1983)
Zostera marina	Chesapeake Bay, USA	20	Dennison et al. (1993)
Zostera marina	Long Island Sound, USA	20	Burkholder and Doheny (1968)
Zostera marina	Kattegat, Denmark	20,1	Ostenfeld (1908)
Zostera marina	Denmark	20,6	Duarte (1991)
Zostera marina	York River, VA (USA)	25	Moore (1991)
Zostera marina	Netherlands	29,4	Duarte (1991)
Zostera marina	Long Island Sound, USA	35,7	Koch and Beer (1996)

Table 1 (*continued*)

Species	Location	% SI	Reference
Zostera marina	California, USA	37	Backman and Barilotti (1976)
Zostera noltii	Spain	2	Peralta et al. (2002)

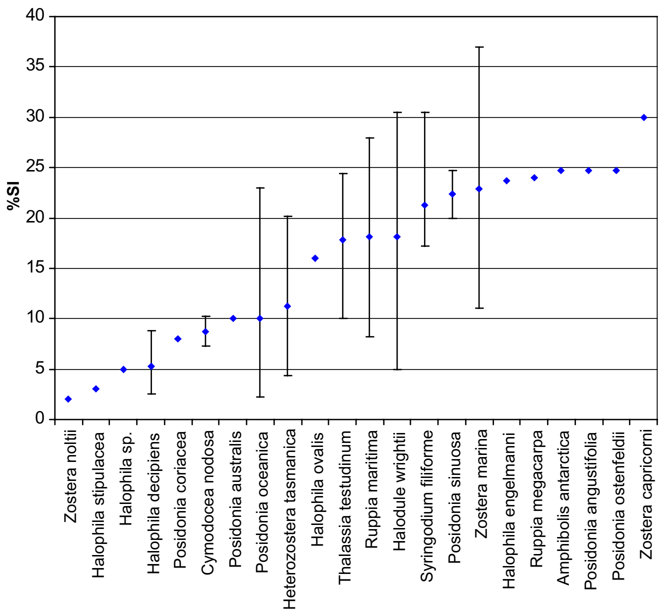

Fig. 1. Range of critical threshold values for light availability (as % surface irradiance SI) reported in the literature for various seagrass species.

sedimentation. Consequences of enhanced sedimentation for seagrass plants depend on several factors such as depth of burial and life history of the species involved (Duarte et al., 1997). Seagrass species that develop vertical shoots (e.g. *Cymodocea*, *Thalassia*, *Thalassodendron*) may respond to fluctuations in sediment depth by modifying their vertical growth to relocate their leaf-producing meristems closer to the new sediment level, but there are limits to the level of sedimentation seagrasses can tolerate (Marba and Duarte, 1994).

Vermaat et al. (1997) reported sedimentation rates of 10–13 cm yr^{-1} as maximum threshold value of what seagrasses in the Philippines and Spain can survive. Manzanera et al. (1995) reported significant mortality of shoots of the seagrass *Posidonia oceanica* in response to experimental over-sedimentation, even at moderate burial (ca. 5 cm). Mills and Fonseca (2003) observed >50% mortality of *Zostera marina* in field burial treatments of 4 cm (corresponding with 25% of plant height) for 24 days. Plants responded similarly to burial in either sand or silt. Plants buried 75% or more of their height (16 cm) experienced 100% mortality.

An overview of values reported in literature for maximum allowable sedimentation rates for seagrasses is presented in Table 3.

In general, it is difficult to separate the effects of turbidity and sedimentation in field studies. Settlement of suspended material on leaf blades of seagrasses may interfere significantly with photosynthesis, and appears especially significant in low wave energy environments where fine sediments are present and can settle out (Shepherd et al., 1989). The impact of sedimentation is often increased where epiphytes are abundant on seagrass leaves (for instance under nutrient enriched conditions) because epiphitized leaf blades collect a greater amount of sediment. In the case of eelgrass (*Zostera marina*) blades and epiphytes then appear dull brown coated with a fine layer of sediment, and they often sink to the bottom (Short et al., 1989).

An indication of the duration that seagrasses can tolerate high rates of sedimentation was revealed by field experiments in Spain. Artificial burial of the seagrass *Posidonia oceanica* with as much as 15 cm of sediment caused 100% mortality after 200–300 days (Manzanera et al., 1995). Sudden burial of *Cymodocea nodosa* with 5 cm of sediment resulted in 90% mortality after 35 days, although some individual shoots of this species were able to survive burial as great as 6 cm (Marba and Duarte, 1994).

Experimental burial of a mixed species seagrass meadow in the Philippines with varying amounts of sediment resulted in major differences in species response (Duarte et al., 1997). *Thalassia hemprichii* and *Cymodocea rotundata* showed a sharp decline in shoot density even at moderate burial treatment with still no recovery 2 months after

Table 2
Duration of time that seagrass species can survive in light intensities below their minimum light requirements

Species	Light availability	Period survived (month)	Reference
Halodule pinifolia	0	3–4	Longstaff and Dennison (1999)
Halodule wrightii	13–15% SI	9	Czerny and Dunton (1995)
Halophila ovalis	0	1	Longstaff et al. (1999)
Heterozostera tasmanica	9% SI	10	Bulthuis (1983)
Heterozostera tasmanica	2% SI	2–4	Bulthuis (1983)
Posidonia sinuosa	12% ambient	24	Gordon et al. (1994)
Thalassia testudinum	10% SI	11	Czerny and Dunton (1995)
Zostera capricomi	5% SI	1	Grice et al. (1996)
Zostera noltii	<2% SI	0.5	Peralta et al. (2002)

Table 3
Critical thresholds of seagrasses for sedimentation (cm/year)

Species	Location	Sedimentation (cm/yr)	Reference
Cymodocea nodosa	Mediterranean (Spain)	5	Marba and Duarte (1994)
Cymodocea rotundata	Philippines	1.5	Vermaat et al. (1997)
Cymodocea serrulata	Philippines	13	Vermaat et al. (1997)
Enhalus acoroides	Philippines	10	Vermaat et al. (1997)
Halophila ovalis	Philippines	2	Vermaat et al. (1997)
Posidonia oceanica	Mediterranean (Spain)	5	Manzanera et al. (1995)
Zostera noltii	Mediterranean (Spain)	2	Vermaat et al. (1997)

burial. *Halodule uninervis*, *Syringodium isoetifolium* and *Cymodocea serrulata* showed an initial decline in shoot density followed by recovery. *Enhalus acoroides* maintained shoot density at all burial treatments and only showed some evidence of decline by the end of the experiment. *Halophila ovalis* showed an opportunistic growth in plots receiving 4–8 cm of sediment, reaching shoot densities well in excess to those of control plots (Duarte et al., 1997).

Sediment conditions (silt and clay content, organic matter and sulfide concentration) can be an important factor limiting seagrass distribution (Koch, 2001), as supported by observations in Southeast Asia where both species diversity and leaf biomass of seagrass communities declined sharply when the silt and clay content of the sediment exceeded 15% (Terrados et al., 1998). Under conditions of high light availability, however, major changes in sediment conditions associated with siltation may not negatively affect seagrass plants but instead enhance their growth by increasing the availability of nutrients, as revealed by recent experiments with *Cymodocea rotundata* in the Philippines (Halun et al., 2002).

Clarke (1987) undertook a series of field-based burial experiments on seagrasses along the Adelaide coast, which demonstrated that, as long as the sediments remained aerobic, *Amphibolis* plants were unaffected in terms of growth rate by burial up to 10 cm of sediment. This was contrasted with *Posidonia angustifolia*, which demonstrated an inverse relationship between growth and depth of burial, unless conditions were anaerobic, causing mortality within 2 weeks (Clarke, 1987). *Zostera tasmanica* appears to be particularly vulnerable to high deposition environments (esp. in the intertidal) as the leaves are quickly coated with sediment (Clarke and Kirkman, 1989). Shepherd et al. (1989) raised the possibility that the loss of 445 ha of *Z. tasmanica* in northern Adelaide waters between 1965 and 1985 was due to sediment accretion.

Seagrasses are also likely to be affected by the nature of the sediments that are deposited, which may bring with them pollutants or a high nutrient load. Furthermore, the redox state of sediments may be altered if there is a high organic load.

5. Seagrass recovery

Despite the known causes of widespread seagrass loss, few studies documented post-disturbance recovery rates of seagrasses (Campbell and McKenzie, 2004). The paucity of data on rates and extent of recovery of seagrass meadows is often due to the lack of data from long-term monitoring programmes and because many seagrass meadows have either failed to recover or taken many years to recover following stress from declining water quality (Short and Wyllie-Echeverria, 1996). In areas disturbed by dugong grazing, propellor scars and other small-scale disturbance, recovery can occur within weeks to months (Williams, 1988; Preen, 1995; Rasheed, 1999). Recovery of subtidal seagrass meadows from large-scale disturbance has been shown to take 2–4 years (Preen et al., 1995) or more than 5 years (Birch and Birch, 1984; Onuf, 2000; Blake and Ball, 2001; Frederiksen et al., 2004; Sheridan, 2004). Often, denuded areas may not recover for many decades because of chronic turbidity due to continual resuspension of unconsolidated sediments (Thorhaug and Austin, 1976). When water quality conditions do not return to their original state, recovery of subtidal seagrass may not occur at all (Giesen et al., 1990).

Campbell and McKenzie (2004) reported on the loss and subsequent recovery of approximately 2000 ha of intertidal *Zostera capricorni* beds from Great Sandy Strait in Queensland, Australia, following substantial flooding of the Mary River in 1999. Whereas 95% of the seagrass meadows in this region were lost within 6 months following the flood due to 2–3 fold increases in turbidity and nutrient concentrations, full recovery (through recolonization from seed banks) occurred within 2 years of initial loss (Campbell and McKenzie, 2004). Recovery of 2000 ha of primarily *Halodule wrightii* due to improved water quality conditions has been reported for Tampa Bay, Florida (Johansson and Lewis, 1992; Lewis et al., 1998). Approximately 1000 km^2 of seagrasses in Hervey Bay, Australia, were lost in 1992 after two major floods and a cyclone within a three-week period, which caused a persistent plume of turbid water. The deepwater seagrasses apparently died from lack of light from the floods. Heavy seas also uprooted seagrass in shallow waters. Subtidal seagrasses (below 5 m deep) started to recover within two years. Intertidal seagrasses only started to recover after four to five years and did not fully recover until December 1998 (Coles et al., 2003). Deterioration of water quality in the Gulf of Adelaide (Australia) from sewage effluents, sewage sludge and stormwater discharges, caused the loss of more than 4000 ha of seagrass between 1969 and 1996 (EPA, 1998).

No significant recovery has been observed to date and losses are continuing, despite some improvements in sludge outfalls.

Variation between different seagrass species in their ability to endure and recover from periods of reduced light is related to their differing morphological and physiological characteristics (Chesire et al., 2002). These characteristics represent different strategies for survival in the face of stress or disturbance. Smaller fast growing (short-lived) species such as *Halophila ovalis* or *Halodule wrightii* do not endure long once environmental conditions are beyond that to which they can adapt, but they tend to recolonize more quickly following an impact. Larger seagrass species such as *Thalassia* or *Posidonia* sp. tend to have greater stored reserves that can be mobilised to sustain the plant temporarily during periods of reduced light (below their minimum light requirements). These species tend to be slow growing, long-lived and therefore represent a resilience strategy, being more resistant to short-term to medium-term disturbances. If, however, the impact persists to the point where these plants have depleted all their reserves, they die. Once lost, recolonization of these species is unlikely or at best slow (Chesire et al., 2002).

6. Scale of damage to seagrass beds from dredging

An overview of 45 documented cases of dredging operations in or near/around seagrass areas, including scale of damage (ha) and mitigating measures applied (if any), is presented in Table 4. A total of 26 out of the 45 case studies presented, together account for a total loss of 21,023 ha of seagrass beds due to dredging and associated activities during the past 50 years. A further 12 case studies reported adverse (in some cases catastrophic) impacts from dredging operations on seagrasses, but did not quantify the total area lost. In the remaining seven case studies, no significant impacts of dredging on nearby seagrass beds were reported. Most of the reported case studies were in Australia (15) and USA (14), with the rest (16) scattered over Europe, Asia, Caribbean and the Middle East.

There must be many more cases of seagrass loss associated with dredging operations worldwide which are mostly – if at all – reported in gray literature and EIA reports, including confidential documents or reports in other languages, access to which is limited. The actual scale of dredging damage to seagrasses worldwide can therefore safely be assumed to be much greater. For example, recent large-scale dredging and land reclamation works in Singapore covering over 10,000 ha (De Jong et al., 2005) are likely to have caused damage to seagrass beds, but this has not been documented. Dredging to purposely remove "unwanted" seagrass vegetation is commonly practised in the Maldives at resorts without restriction (Iain Benson, pers. comm., May 2005). Seismic explorations for oil in Belize on turtle grass flats (several decades ago) resulted in permanent dotted lines across several of the grass flats, each dot the size of a 2-car garage (Anonymous, in lit.).

More recently, a series of some of the largest land reclamations in recent history have been initiated in Dubai, United Arab Emirates (De Jong et al., 2005). The dredging and dumping operations that are necessary for these extreme reclamations in Dubai (covering well over 20,000 ha), apparently permitted under governing national legislation, and several other recent reclamation and coastline modification projects elsewhere in the Middle East, are likely to affect large areas of sensitive marine habitats including seagrass beds (B. Riegl., pers. comm., May 2005; Purkis and Riegl, 2005).

Nevertheless, the selection of case studies presented here is considered representative of the scale and nature of damage commonly occurring. Other factors such as land reclamation, port construction, beach nourishment and poor catchment management also contributed to seagrass decline. Yet in all of these cases, dredging reportedly played a key role.

Two of the largest losses, i.e. 15,000 ha in Laguna Madre (Texas, USA) and 'thousands of hectares' in Moreton Bay (Australia), have occurred before 1990. Most of the more recent losses in Australia and USA are substantially smaller in scale and 6 of the 7 no-impact case studies were recent (post-1990). Data from European countries and elsewhere are too few to detect similar trends.

As the various case studies reveal, the extent of damage to seagrasses is not simply a function of the size and scale of the dredging operation alone, but also depends on the proximity to the seagrass bed, type and composition of the sediment, the way dredging equipment is used, mitigating measures applied, and so forth.

The scale of predicted damage to seagrass vegetation and cumulative effects can be issues of concern in the permit process for dredging and sand mining. According the Florida Fish and Wildlife Conservation Commission, for example, over 200 permit requests are submitted each year for small-scale dredging and constructions in Florida that may affect very small areas (often below 100 m^2) of seagrass vegetation (FFWCC, 2001; Kirsch et al., 2005). No amount of seagrass loss, no matter how small, is allowed to happen in Florida without formal permits being issued.

In several cases in the USA, applicants have attempted to seek dredging permits to fit channels into gaps in seagrass beds. Yet, opponents have argued (successfully in some cases) that seagrass meadows are known to migrate across the landscape and dredging below the compensation depth in a gap would eliminate potential seagrass habitat in the future (Jud Kenworthy, pers. comm., April 2005). Concern over predicted impacts on areas that constitute potential seagrass habitat but are currently unvegetated is sometimes considered legitimate in areas where major efforts are underway to restore seagrass vegetation, as noted for Tampa Bay (FFWCC, 2001) and the Dutch Wadden Sea (Van Katwijk, pers. comm., December 2004).

Not all observed reductions in seagrass cover in the immediate vicinity of dredging sites are necessarily the

Table 4
Overview of case studies on dredging impacts on seagrasses

Country	Location	Year	Activity/Purpose	Scale of impact/damage	Mitigation/Response	Reference
Australia	Botany Bay, New South Wales	1942–1984	Widespread dredging, along with poor catchment management and uncontrolled effluent disposal	Loss of **257 ha** of seagrass beds (*Posidonia australis*, *P.sinuosa*)	None reported	Walker and McComb (1992), Larkum and West (1990)
Australia	Success Bank and Parmelia Bank, Western Australia	1950s–2002	Commercial dredging for mining of calcium carbonate sands (shellsand) for production of lime (for mining industry) by Cockbum Cement	Loss of **232 ha** of seagrass (*Posidonia coriacea, Amphibolis griffithii* and *Posidonia sinuosa*) + additional loss of 168 ha predicted for period 2002–2014	Transplanting seagrass sods using planting machines for rehabilitation	Gordon et al. (1996), Wyllie et al. (1997), Lord et al. (1999), Paling et al. (2001), Walker et al. (2001)
Australia	Southern Bay Islands Region, Moreton Bay, Queensland	1955–2000	Dredging of access channels and marine infrastructure development (canal estate development)	Loss of thousands of hectares of seagrass (*Zostera capricorni*) due to dredging and associated turbidity	None reported	Kirkman (1978), WBM, 2001, Thorogood et al. (2001), Coles et al. (2003)
Australia	Cleveland Bay and Magnetic Island, Queensland	1970s	Capital and maintenance dredging at Ross River mouth and disposal at various dump sites in Cleveland Bay (peak in the early – mid-1970s)	Extensive burial and loss of nearly all seagrass vegetation (possibly several thousand ha according to habitat maps) followed by gradual recovery during 1978–1985	None reported	Pringle (1989)
Australia	Section Bank (Barker Inlet), South Australia	Late 1980s	Channel dredging of Port River	None reported (impact considered acceptable)	None reported (impact considered acceptable)	Chesire et al. (2002)
Australia	Section Bank (Barker Inlet), South Australia	Mid-1980s	Dredging of a trench for the Wasleys to Adelaide Pipeline Looping Project (30–50,000 m^3)	No significant (long-term) effects on seagrass	None reported	Chesire et al. (2002)
Australia	Deception Bay, Queensland	1991–1992	Channel deepening and maintenance dredging of the access channel into Newport Waters Canal Estate	No significant impacts detected	Monitoring (3yrs.) and mapping	Long et al. (1996)
Australia	McArthur River, Northern Territory, Western Gulf of Carpentaria	1994	Capital dredging of 1,250,000 m^3 of sediment for development of trans-shipment facility (incl. large channel, swing basin for berthing)	Loss of **18.95 ha** dense seagrass (direct removal) 3 years of monitoring indicated no further loss along canal edges or adjacent bed	Confined land disposal with 2-stage sedimentation ponds; monitoring of seagrass along channel edges	Kenyon et al. (1999)
Australia	Botany Bay, New South Wales	1994–1995	Dredging and landfill for construction of Sydney airport 3rd runway extension	Loss of **18 ha** of seagrass (*Zostera capricorni*) due to direct removal + additional loss of **5 ha** (*Posidonia* spp.) due to sand relocation for bird habitat reconstruction works	1.8 ha of seagrass transplanted successfully for compensation (pilot trial project)	Lord et al. (1999)
Australia	Port of Karumba, Queensland	1994–2004	Maintenance dredging of port entrance and river channel	No observable impacts on approx. 1000 ha of seagrass within the Port area	Long-term monitoring	Rasheed et al. (2001)
Australia	Fisherman's Island, Brisbane, Queensland	2000	Dredging and filling for the proposed expansion of the Port of Brisbane (dredging of 300,000 m^3)	Direct loss of **90 ha** of seagrass (patchy) predicted	Environmental management plan	POB (2000), BREC (2000)
Australia	Port of Weipa, Queensland	2000–2003	Capital and maintenance dredging of 3,750,000 m^3 to widen and deepen entrance channel and berth facility	Minimal or no impact predicted on 4000 ha of seagrass within Port limits	If visual plume over seagrass persists >6 h dredging to be relocated (+plume modelling)	GHD (2005)

Australia	Owen Anchorage, Cockburn Sound Western Australia	2002–2010	Planned Stage One-Dual Channel Dredging by Cockburn Cement (commercial shellsand mining)	Estimated direct loss of **53 ha** of seagrass (of which 38 ha *Posidonia sinuosa* and *Posidonia australis* +15 ha *Posidonia coriacea* and *Amphibolis griffithii*)	Detailed environmental management plan and transplanting proposed	Lord & Associates (2000)
Australia	Towra Beach, Botany Bay, Sydney	2004–2005	Dredging and filling for the Towra beach nourishment project (60,000 m^3 using cutter suction dredge) + dredging for the parallel runway project	Predicted loss of **3.85 ha** of seagrass (*Zostera capricorni*) due to the nourishment project + loss of **13.73 ha** due to the parallel runway project	Minimize overall seagrass loss and avoiding all *Posidonia* seagrass beds	SMEC (2003)
Australia	Port Philip Bay, Melbourne	2005	Dredging for channel deepening, Port of Melbourne (31.7 million m^3 sediment plus 0.5 million m^3 rock)	No significant impacts on seagrasses expected (20% reduction of primary production acceptable)	Seagrass productivity not to be reduced by more than 20%; turbidity to be kept within thresholds; extensive monitoring program	Edmunds et al. (2004), Pert of Melbourne Corp., 2004, Hart et al. (2004)
Bahrain	Fasht Al-Adhm, east coast of Bahrain (Arabian Gulf)	1985–1992	Dredging and filling associated with various land reclamations along the north-east coast	Loss of 10.2 km^2 (**1002 ha**) of seagrass beds detected from remote sensing imagery	None reported	Zainal et al. (1993)
Bermuda	Castle Harbour, Bermuda	1942–1943	Dredging and fill operation (12–15 million m^3) for a 300 ha land-fill for army station and Bermuda International Airport	Loss of **18.2 ha** of seagrass (*Thalassia testudinum*) due to dredging and associated turbidity	None	Smith (1999), Sterrer and Wingate, 1981
Brazil	Sepetiba Bay, Rio de Janeiro State	1997	Dredging of 20.86 million m^3 of bottom sediment to increase the capacity of the Port of Sepetiba	Accumulation of heavy metals by seagrasses from resuspended contaminated sediments	None reported	Filho et al. (2004)
Denmark	Saltholm and surrounding waters (Øresund)	1995–2000	Dredging and reclamation for the construction of the Øresund fixed link (bridge and tunnel) between Denmark and Sweden	No impacts on eelgrass beds (*Zostera marina*) (zero loss)	Feedback monitoring (stopping the dredging when turbidity thresholds exceeded); strict environmental regulations and extensive monitoring	Thorkilsen and Dynesen (2001), Jensen and Lyngby (1999), Krause-Jensen et al. (2001)
Fiji	Suva region, Fiji Islands	Early 1980s	Commercial dredging of coral sand for cement production (100,000 tonnes dry weight/yr in 1981)	Total destruction of seagrass beds within the dredgepit areas (not quantified) but gradual recolonization of dredged areas over time	Management plan	Penn (1981)
France	Gulf of Porto-Vecchio, Corsica	1970s	Dredging and port construction for Porto-Vecchio's commercial port	Almost complete disappearance of *Posidonia oceanica* beds in far end of Gulf of Porto-Vecchio	None reported	Pasqualini et al. (1999)
Hong Kong (China)	Chek Lap Kok International Airport, Hongkong	1994–1998	Dredging, reclamation and construction works for new international airport	Complete disappearance of seagrass (*Zostera japonica*) but some local recovery of *Halophila ovata*	None reported	Lee (1997), Fong (2000), Fong (2001)
Indonesia	Benoa Bay, Bali	1996–1998	Dredging (50 million m^3) and filling for land reclamation (Bali Turtle Island Development and Bali Benoa Marina)	Substantial loss of seagrass beds (approx. **500 ha**-estimated from habitats and development map)	EIA; Project abandoned after completion of reclamation in 1998 due to financial crisis	Shaw (2000)
Italy	Gulf of Oristano, Sardinia	1970s	Channel dredging and commercial port construction	Substantial loss of *Posidonia oceanica* meadows (approx. **800 ha** estimated from distribution map)	None reported	De Falco et al. (2000)

(*continued on next page*)

Table 4 (*continued*)

Country	Location	Year	Activity/Purpose	Scale of impact/damage	Mitigation/Response	Reference
Italy	Cape Feto, SW Sicily (Mediterranean)	1993	Dredging and fill operation for construction of Italo-Algerian methane gas pipeline	Direct loss of **150 ha** of seagrass (*Posidonia oceanica*) plus indirect effects from pulsed siltation on nearby seagrass meadows	None reported	Di Carlo et al. (2005), Di Carlo et al. (2004), Badalamenti et al. (2006)
Italy	Ischia Island, Gulf of Naples (Tyrrhenian Sea)	2002	Sand extraction for refilling of a beach	Loss of **4 ha** of *Posidonia oceanica* off Ischia Island (direct loss)	None reported	Gambi et al. (2005)
Kenya	Mombasa coastal area	Mid-1990s	Dredging and filling associated with jetty construction by local fishing company	Loss of **2 ha** of seagrass (5 spp.) plus additional (indirect) impacts from associated turbidity	None reported	Wakibya (1995)
Netherlands	Hond-Paap tidal flat, Ems estuary	2002–2003	Dredging and excavation of 250,000 m^3 of sediment for the deepening of an existing gas pipeline	No significant impacts on nearby eelgrass beds (*Zostera marina*)	Restrictions to timing, turbidity plume modelling, EIA monitoring programme	Erftemeijer (2002), Erftemeijer and Wijsman (2003)
Portugal	Rio de Aveiro, Atlantic Ocean	1984–2003	Channel dredging (deepening and widening) of the inlet connecting the Rio de Aveiro estuary/lagoon with the Atlantic Ocean	Loss of 8 km^2 (**800 ha**) of seagrass vegetation (*Potamogeton pectinatus, Ruppia cirrhosa* and *Zostera noltii*) due to indirect effect of dredging on turbidity, resuspension and tidal wave penetration	None reported	Da Silva et al. (2004)
Portugal	Rio Formosa (tidal/coastal lagoon)	Mid-1990s	Dredging of navigation channels and two tidal inlets to facilitate ocean passage and increase tidal circulation	Some seagrass affected (not quantified) (*Cymodocea nodosa* and *Zostera marina*)	Short-term monitoring	Janelle Curtis (in litt)
USA	Boca Ciega and Tampa Bay, Florida	1876–1976	Channel deepening, maintenance dredging, shell dredging and dredging for landfill and construction	Loss of 1400 acres (**567 ha**) of seagrass areas (5 spp.); extremely slow recovery (partly due to loss of offshore sandbars)	Complete halt of open water spoiling in Tampa Bay since 1973; use of upland disposal sites (at increased costs)	Lewis (1976), Taylor and Saloman (1968), Fonseca (2002), Lewis et al. (1998)
USA	Indian River Lagoon, Florida	1940–1992	Maintenance dredging and creation of spoil islands	Burial of seagrasses by creation of spoil islands and further losses due to turbidity from dredging (but some recolonization by *Halodule wrightii*)	None reported	Fletcher and Fletcher (1995), Brown-Peterson et al. (1993)
USA	Laguna Madre, Texas	1965–1988	Maintenance dredging (every 2–5yrs) of navigation channels and disposal of spoil (elsewhere in lagoon)	Loss of **15,000 ha** of seagrass beds (*Halodule wrightii*) from all waters deeper than 1 m due to turbidity caused by dredging/disposal with very little recovery	Various management actions and research on seagrass recovery	Onuf (1994), Quammen and Onuf (1993), Pulich and White (1991)
USA	Port of Miami, Florida	Early 1980s	Channel deepening, dredging of turning basin and filling of an artificial island as part of the expansion of the Port of Miami	Loss of **33 ha** of seagrass (+ additional loss of 69 ha of potential seagrass habitat)	The permit required replanting of 102 ha of seagrass to mitigate for losses; initial success very poor (2.4 ha survived)	Gaby et al. (1986), Lewis (1987)
USA	Key Biscayne, Florida	1985	Dredging and placement for beach nourishment of 3.9 km of Atlantic beaches	Burial and loss of **10.5 ha** of seagrasses	Salvage of seagrasses for use in mitigation of another dredging project (Port of Miami)	Gaby et al. (1986)
USA	Great Bay estuary, New Hampshire	<1993	Dredging and construction for expansion of the New Hampshire Port	Loss of **2.5 ha** of seagrass (Zostera *marina*) from direct and indirect impacts of dredging	Restoration of 2.5 ha of seagrass bed elsewhere in the estuary + long-term monitoring	Short et al. (2000), Davis and Short (1997)

USA	Laguna Madre, Texas	1994–1995	Maintenance dredging and disposal of dredged material (total 715.500 m^3) at six sites in the lagoon	Burial of seagrass vegetation at disposal sites; significant recovery (*Halodule wrightii*) within 3 yrs	Monitoring of recovery rate	Sheridan (2004)
USA	Indian River Lagoon, Florida	1996–1997	Fort Pierce cargo port extension, incl. deepening of the harbour and deepening and widening of the entrance channel	Loss of 39.3 acres (**16 ha**) of seagrass (*Halophila johnsonii*) + indirect secondary impacts from turbidity on highly productive seagrass beds (400 acres) nearby	None reported	MacArthur Report (1997), Virnstein and Morris (1996)
USA	Delmarva Peninsula, Maryland and Virginia	1996–1999	Hydraulic dredging and modified oyster dredging for clams (fishing)	**1257 ha** of seagrass affected/ damaged with scars; slow recovery taking >3 years	Adoption of legislation for the protection of most seagrass beds in Virginia (1997) and Maryland (2002) not allowing clam dredging in seagrass beds	Orth et al. (2002)
USA	Tampa Bay, Florida	1999–2000	Dredging for navigation and berth improvements as part of Port Manatee expansion project	Loss of 5.33 acres (**2.2 ha**) of seagrass (*Thalassia testudinum. Halodule wrightii* and *Syringodium isoetifolium*)	Transplanting of 17.57 acres (=7.1 ha) of seagrass (mainly *Halodule wrightii*) achieved within 3 years	Environmental Affairs Consultants (2005)
USA	Cape Ann peninsula, Massachusetts, Manchester-on-the-Sea	2001	Channel maintenance dredging to improve harbor access	Initial loss of seagrass in dredged channel areas; good post-dredging recovery within 3–4 years	Minimizing duration; seasonal restrictions; no-spud zone; limit over-dredge quantities; 5-year seagrass monitoring program	Peña (2005)
USA	Emeryville Flats, San Francisco Bay	2001–2002	Dredging, filling and construction related to the San Francisco – Oakland Bay Bridge project	58% decline in vegetation cover representing a loss of **8.3 ha** of seagrass (*Zostera marina*)	Not available	Merkel (2003)
USA	Miami Harbor area, Biscayne Bay	2002–2003	Dredging for widening of entrance channel and turning basin at Miami Harbor	Loss of 6.3 acres (2.6 ha) of seagrass by direct removal and subsequent sloughing	Replanting of 6.3 acres of seagrass (*Halodule wrightii* + 3 other spp.) on former borrow areas in Biscayne Bay	Dial Cordy and Assoc., 2002
USA	Scituate Harbor, MA, New England	2002–2003	Navigation maintenance dredging of small boat harbor	Loss of 1.8 ha of eelgrass (*Zostera marina*); some subsequent recovery within 2 years	No dredging allowed near dense eelgrass; use of silt curtains; seagrass monitoring	Sabol et al. (2005), Sabol and Shafer, 2005
US Virgin Islands	Water Bay, St. Thomas, Virgin Islands	1969	Dredging for navigation and boating (removal of 600,000 cubic yards of material from Water Bay)	Mass mortality/loss of seagrasses (*Thalassia testudinum*) and corals due to meachanical removal, sedimentation and turbidity	None reported	Van Eepoel (1969)

result of dredging-induced turbidity. Indeed, distinguishing effects of anthropogenic disturbances from natural dynamics in estuarine and marine environments can be a challenge (Montagna et al., 1998). Recent field monitoring at two sites in New England and Florida indicated that dredging-induced turbidity did not extend to nearby seagrass beds, and that locally observed seagrass decline must have been due to some other (natural) disturbance (Sabol and Shafer, 2005).

7. Mitigating measures

A number of management techniques and mitigation measures have been developed, such as tidal dredging, physical barriers, environmental dredging techniques and so forth, which may be used to mitigate effects of dredging on sensitive organisms or ecosystems (Smits, 1998). In hydraulic dredging techniques, the dredging rate can be adapted by increasing the amount of water pumped up relative to the amount of sediment that is dredged, which can help to reduce the extent of turbidity plumes. Examples of other environmental dredging equipment include encapsulated bucket lines for bucket chain dredgers, closed clamshells for grab dredgers, auger dredgers, disc cutters, scoop dredgers and sweep dredgers (all modified cutter dredgers). A more recent development is sub-suction dredging (e.g. BeauDredge, Multilans), which allows for lowering of the seafloor by extracting sediment from deeper layers without disturbing the top layer.

Mitigating measures applied in the various case studies (Table 4) include confined land-disposal, EIA, turbidity modelling (plume prediction), turbidity thresholds, limits to allowable reduction in seagrass productivity, minimizing duration of dredging, seasonal restrictions (e.g. avoiding seagrass flowering periods), limiting over-dredge quantities, establishment of no-spud zones, use of silt screens, prohibiting dredging near dense seagrass areas, stopping dredging when turbidity thresholds are exceeded, seagrass monitoring and mapping, research on seagrass recovery, salvage of seagrasses for use in transplantation to mitigate losses (Lewis, 1987), post-dredging seagrass restoration (Lewis, 1987; Fonseca et al., 2002), and adoption of legislation banning the use of certain (clam) dredging methods.

In the case of the Øresund Fixed Link (Denmark), a whole range of technical and environmental aspects of the dredging operation were integrated with the contractual commitments of the contractor to prevent impacts on eelgrass beds in the area (Jensen and Lyngby, 1999). Two major tools were introduced to ensure that spill was kept below the limits necessary to fulfill the environmental objectives and criteria of the project: (1) the contractor was held responsible through his contract for keeping the spill below specified limits varying in time and space, taking into consideration environmentally sensitive periods and areas; (2) a feedback-monitoring programme was implemented to covering sediment spill, dispersal thereof, and biological key variables representing the most sensitive benthic communities. Dredging was stopped temporarily during peak currents for approximately 20 times to keep within these environmental restrictions (Thorkilsen and Dynesen, 2001). These measures helped to ensure that there were no significant impacts from dredging and construction activities on the eelgrass beds (Krause-Jensen et al., 2001).

In at least one case, silt curtains have been used to reduce impacts on seagrasses (Sabol et al., 2005). Although the efficacy of silt curtains in reducing dredging-induced turbidity and siltation impacts on the seagrass beds was not evaluated, the authors note that the design of the curtains installed by the contractor may have been inadequate for the hydrodynamic conditions prevalent in the study area. High tidal flow resulted in breakage of anchor lines and rupture of the seams of the curtains (Sabol et al., 2005).

Installation of physical barriers such as silt screens is often a difficult operation, demanding great skill and experience on the part of the dredging contractor to avoid leakage through the curtain. Enclosure of dredging equipment with a silt screen is restricted mainly to the use with stationary dredgers using pipeline discharge methods, and is always accompanied by some degree of leakage underneath. Protection of an environmentally very sensitive area with silt screens may in some cases be viable, but only if the physical conditions of the site (esp. waves and currents) allow their effective use (USACE, 2005). Use of a silt screen, however, clearly limits the output level of the dredger, lengthens the execution period, and increases the costs of the project (Smits, 1998).

Impact prediction (e.g. through plume modelling and/or habitat modelling) and turbidity monitoring have proven to be successful tools in preventing or minimizing environmental impacts on seagrasses from dredging operations (Jensen and Lyngby, 1999; Thorkilsen and Dynesen, 2001; Krause-Jensen et al., 2001; Erftemeijer, 2002; Erftemeijer and Wijsman, 2004). A new method for synoptic real-time nowcasting, hindcasting and short-term forecasting of turbidity by combining information from remote sensing data, water quality modelling of sediment transport and in situ data using data-model integration (DMI) techniques, may prove to be an even more sophisticated, yet practical tool for use by the dredging industry in curbing environmental impacts (Erftemeijer et al., 2002; Tatman et al., 2005).

8. Regulation of dredging in seagrass areas

Specific regulations to protect seagrasses are few. Although marine protected areas (MPAs) are rarely established specifically to conserve seagrasses, there are 247 MPAs worldwide known to include seagrasses (Spalding et al., 2003). In addition to designation of MPAs, other legal measures have proved beneficial to seagrasses in some places, although seagrasses themselves are rarely singled out as the object of protection. In Queensland (Australia), for example, all seagrasses and other marine plants are specifically protected under the Fisheries Act of 1994, for protection of commercial and recreational fishing activities (Spalding et al., 2003). In the Mediterranean, *Posidonia oceanica* meadows are accorded priority protection under Annex 1 to the EU Habitats Directive, while 3 of 5 Mediterranean seagrass species are described as endangered in the SPA/BD Protocol of the 1995 Barcelona Convention (EEA, 2005). Since *Posidonia oceanica* meadows are particularly vulnerable to bottom-disturbing activities, some countries like Spain have severely limited dredging operations susceptible to alter *Posidonia* communities along the coast of Spain (Eurosion, 2004).

Both dredging and disposal operations are increasingly regulated more strictly with regards to their environmental impacts. In addition to national and regional legislation and policies, some useful general guidelines have been drawn up within the framework of international and regional conventions. The London Convention (1972) adopted the dredged material assessment framework (DMAF), a widely reviewed and accepted approach to the assessment of suitability of dredged material for disposal at sea. The OSPAR Convention (1992) adopted the OSPAR Guidelines for the Management of Dredged Material (OSPAR, 1998) and more recently produced a background document on 'Environmental Impacts to Marine Species and Habitats of Dredging for Navigational Purposes (OSPAR, 2004). Some other helpful documents include the 'Good Practice Guidelines for Ports and Harbours operating within or near UK European Marine Sites' (ABP Research, 1999), the 'Guidelines for Dredging' of EPA Victoria in Australia (EPA, 2001) and the series on 'Environmental Aspects of Dredging' issued by the Central Dredging Association (CEDA) and International Association of Dredging Companies (IADC) (Jensen and Mogensen, 2000).

In the United States, there are multiple levels of regulation of both direct and indirect effects of dredging and water quality degradation on seagrasses. At national level, the US Army Corps of Engineers has primary jurisdiction of dredging in "navigable waters", which includes essentially all marine and estuarine waters in the USA. Seagrass beds are regulated as "special aquatic sites" not as wetlands, but the same laws that apply to wetlands under Section 404 of the so called Clean Water Act (Federal Water Pollution Control Act, Public Law 92–500), originally passed by the US House and Senate in 1972, and modified since, apply regarding application for permits to impact any site with seagrasses. Permit applications are processed by the Corps, but are reviewed by other federal agencies, including the US Fish and Wildlife Service, National Marine Fisheries Service and US Environmental Protection Agency (EPA). EPA also has veto authority on any attempt by the Corps to override its recommendations for permit denial, although the power has been rarely used. EPA also regulates water quality directly under the same Clean Water Act with authority to issue permits to dischargers and limit quantities of pollutants, including suspended particles and nutrients, discharged to waters of the USA.

In addition, all of the 51 states of the USA, have individually some type of environmental pollution prevention laws, some stronger than others. In many states, like Florida and California, the Corps will not issue a federal 404 permit until the state issues a "water quality certification" that a proposed project, including dredging in or around a seagrass meadow, will not violate certain specific water quality criteria. Further some subdivisions of state government, such as counties or cities may have another set of regulations protecting wetlands in general and seagrasses specifically in coastal areas. All of these regulations require that permits be reviewed and if issued, include stringent monitoring of survival of seagrasses around dredging sites, and water quality monitoring during dredging. Turbidity, suspended particulate load, light penetration, dissolved nutrients and dissolved oxygen are common parameters that must be monitored and reported, and if exceedances occur, dredging must be stopped until monitoring confirms a return to background conditions.

In Australia, dredging and disposal of dredged spoil is governed by the Environment Protection Act 1981. In addition, the Great Barrier Reef Marine Park Act 1975 includes further provisions to assess and manage environmental impact of coastal development activities such as dredging. General dredging and sea dumping permits are subject to conditions which may typically include restrictions to the size of the impacted zone, limitations to a certain period of the year, turbidity limits and tidal restrictions (EPA, 2001). Turbidity limits are generally expressed in terms of maximum allowable exceedance (in %) above the best estimates of natural ambient turbidity. If this target is exceeded there are limits to the duration of plumes (e.g. not allowed to exceed an aggregate of four days in any five-day period, or 90% of any 10-day period). If such periods are exceeded, this will trigger a management response, such as temporary cessation or modification of dredging or disposal works or further restrictions on methods and location of future operations. Turbidity limits may be modified during the course of the dredging operation after consideration of monitoring results. Conditions also include the need for trial dredging, compliance- and effects monitoring (esp. of turbidity plumes and background turbidity), and monitoring and mapping of species composition and abundance of seagrass beds in the affected area. In most cases, a technical advisory and consulative committee is established that sets up and agrees on monitoring programmes, decides on the need and frequency of sampling and is allowed to make additional recommendations that will help to minimize environmental impacts of the dredging operations (EPA, 2001). Regulations may also include the need to rehabilitate affected seagrass areas.

Establishing a reasonable background turbidity level can be challenging, particularly given the variable nature of the ambient state. With a highly time variable background condition, some ports have adopted an approach of real-time comparison between plume measurements over sensitive areas with ambient conditions, whilst others continue to use an historic estimate based on regular monitoring of ambient conditions. Whilst dredging may cause an above average elevation of turbidity over seagrass, these elevations may in many instances be within the long term background range for the area and short-lived when compared to a frequent and naturally occurring event such as a significant rain event during the wet season. It can therefore not be assumed that transitory dredge plumes in excess of an area's average turbidity would necessarily cause significant impacts on seagrasses. Therefore, authorities increasingly take natural variability in background turbidity into consideration.

Historically, the management approach in the USA (with strong 'riparian' property rights anchored in constitutional laws) focused primarily on remediation (compensating for damage to be incurred to seagrass) with regulations applying to all dredging operations, even very small ones. In Australia, the approach has been more or less that of a zero-loss strategy, preventing or minimizing impacts on seagrass, with planned dredging operations being assessed following a case-by-case approach. Since about 15 years ago, the situation in the USA has changed, partly as a result of a growing awareness of economic losses associated with damage to seagrass beds. Now dredging in or near seagrass beds is very strictly controlled, and permits are hard to get, even for minor impacts (0.1 ha). Part of the issue is whether you can adequately mitigate or compensate for seagrass impacts. Most such projects have failed in the past (Lewis, 1987).

There is suspicion of potential bias and lack of objectivity in the licensing process for dredging permits. A recent study into sustainability of UK offshore dredging for marine aggregate mining (Olsen, 2005) noted that the vested economic interests of applicants, license granting bodies, license owners and monitors of the dredging are likely to affect objectivity in impact assessments submitted in the licensing procedure. Environmental impact assessment studies of large-scale land reclamation schemes in parts of the Middle East are sometimes shrouded in secrecy or are in some cases conducted only after reclamation has already been implemented.

9. Estimated costs

Stricter regulations, tighter control measures, proper enforcement and detailed monitoring, together with proper impact assessment, application of wide-ranging mitigating measures and the development of new environmentally friendlier dredging techniques appear to increasingly help in efforts to prevent or minimize adverse environmental impacts on seagrasses. Estimates of the extra costs of such mitigating measures (due to longer duration and special equipment needs) and/or compensation payments for damage incurred by dredging contractors are difficult to obtain. It appears reasonable, however, to assume that costs incurred in efforts aimed at preventing or minimizing seagrass damage are probably negligible in comparison with costs of seagrass restoration programmes, which often appear to have limited success.

Fonseca et al. (2002) discussed the ecological restoration of seagrasses including the success rate for seagrass mitigation undertaken for permitted losses of seagrasses, or as court ordered restoration after illegal damage. They noted that while seagrass restoration or mitigation can be successful, many errors occur in site selection in particular, and partial or complete failures in such attempts has been common. Citing a particular example of a court-ordered seagrass restoration project, they also note that successful efforts can be very expensive. The particular example they used costed US$ 630,000 per hectare (1996 costs) including site surveys, monitoring and reporting. Lewis et al. (2006) describe a US$ 6 million project that had only achieved approximately 1.5 ha of success at the time of reporting. A recent €900,000 eelgrass restoration programme in the Dutch Wadden Sea has achieved little success after 4 years of re-introduction and transplantation trials (Bos and Van Katwijk, 2005). The costs of two successful seagrass restoration projects in the USA ranged between 200,000 and 500,000 US$ per ha (Davis et al., 2002; Lewis et al., 2006). In their review of techniques for restoration and substitution of ecosystem services of tropical coastal ecosystems (including seagrass beds), Moberg and Rönnbäck (2003) conclude that it is probably always cheaper to aim at preserving ecosystem functioning than trying to restore or substitute them when they have been degraded or lost.

10. Discussion and conclusions

Although there clearly are a large number of reports that have documented adverse impacts on seagrass beds from dredging and sand-mining operations, there are several other (mostly recent) cases that reported no impacts on nearby seagrasses at all. There appears to be an increasing awareness among dredging contractors and regulatory bodies on the economic and ecological value of seagrass beds and the importance to make a concerted effort to minimize impacts on these sensitive systems. The various case studies from the USA and Australia suggests that the largest impacts have mostly been in the past. As a result of stricter regulations and enforcement by relevant authorities, recent large-scale dredging operations take various precautions and mitigating measures to keep impacts at a minimum. Elsewhere, experiences seem to vary between countries and from case to case.

As some of the case studies have shown, even large-scale dredging operations do not always cause significant impacts to seagrass beds. This may not necessarily be the result of strict environmental regulations and mitigating measures, but is sometimes a direct function of local environmental conditions.

Development of criteria to protect seagrasses must acknowledge that seagrasses tolerate periods of naturally high turbidity and can withstand some increase in the frequency of turbid events. Turbidity is unlikely to be continuous at any particular site particularly due to changes in wind and tidal conditions but also due to changes in dredge location and dredging rate. In areas that experience large natural fluctuations in background turbidity (esp. in estuarine environments), seagrasses and other benthic communities often display a greater resilience than in areas where natural turbidity fluctuations are minimal.

Nearshore seagrass communities, like other marine ecosystems, are commonly thought to be largely static entities, with predictable, seasonal changes. Increasingly, however, studies examining interannual variability in seagrass and other macrophyte communities remind us that this is not necessarily the case. Seagrass patches may come and go, may change position or density, and their associated fish communities may be different from year to year (Hemminga and Duarte, 2000). Consequently, what we observe in one year may or may not hold true in subsequent years. Given this potentially high variability, it is especially important to use caution when basing long-term management decisions on short-term observations. Ecosystems may not function or behave as expected when we base our expectations on a mere snapshot of a constantly changing entity (Weitkamp, 1998).

Therefore, copying of dredging criteria used in one geographic area to a dredging operation in another may in some cases lead to exaggerated limitations resulting in unnecessary costs and delays in dredging operations, or in other cases could prove damaging to seagrass ecosystems. Meaningful criteria to limit the extent and turbidity of dredging plumes and their effects will always require site-specific evaluations and should take into account the natural variability of local background turbidity.

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References

Abal, E.G., Dennison, W.C., 1996. Seagrass depth range and water quality in Southern Moreton Bay, Queensland, Australia. Marine and Freshwater Research 47, 763–771.

ABP Research, 1999. Good practice guidelines for ports and harbours operating within or near UK European marine sites. English Nature, UK Marine SACs Project, 20 pp.

Backman, T.W., Barilotti, D.C., 1976. Irradiance reduction: effects on standing crop of eelgrass *Zostera marina*. Marine Biology 34, 33–40.

Badalamenti, F., Di Carlo, G., D'Anna, G., Gristina, M., Toccaceli, M., 2006. Effects of dredging activities on population dynamics of *Posidonia oceanica* (L.) Delile in the Mediterranean sea: the case study of Capo Feto (SW Sicily, Italy). Hydrobiologia 555, 253–261.

Batiuk, R.A., Bergstrom, P., Kemp, M., Koch, E., Murray, L., Stevenson, J.C., Bartleson, R., Carter, V., Rybicki, N.B., Landwehr, J.M., Gallegos, C., Karrh, L., Naylor, M., Wilcox, D., Moore, K.A., Ailstock, S., Teichberg, M., 2000. Chesapeake Bay Submerged Aquatic Vegetation Water Quality and Habitat based Requirements and Restoration Targets: A Second Technical Synthesis. CBP/TRS 245/00 EPA 903-R-00-014. U.S. EPA Chesapeake Program, Annapolis, Maryland.

Beal, J.L., Schmit, B.S., 2000. The effects of dock height on light irradiance (PAR) and seagrass (*Halodule wrightii and Syringodium filiforme*) cover. In: Bortone, S.A. (Ed.), Seagrasses: Monitoring, Ecology, Physiology, and Management. CRC Press, Boca Raton, Florida, pp. 49–63.

Beer, S., Waisel, Y., 1982. Effects of light and pressure on photosynthesis in two seagrasses. Aquatic Botany 13, 331–337.

Bell, J.D., Pollard, D.A., 1989. Ecology of fish assemblages and fisheries associated with seagrasses. In: Larkum, A.W.D., McComb, A.J., Shepherd, S.A. (Eds.), Biology of Seagrasses. A Treatise on the Biology of Seagrasses with Special Reference to the Australian Region, Aquatic Plant Studies 2. Elsevier, Amsterdam, pp. 565–609.

Birch, W.R., Birch, M., 1984. Succession and pattern of tropical intertidal seagrasses in Cockle Bay, Queensland, a decade of observations. Aquatic Botany 19, 343–367.

Blake, S., Ball, D., 2001. Victorian marine habitat database seagrass mapping of Westernport. Marine and Freshwater Resources Institute report No. 29, 36 pp.

Bogers, P., Gardner, J., 2004. Dredging near live coral. Paper presented at the 17th World Dredging Congress, 27 September–1 October 2004, Hamburg, Germany. WODCON XVII 2004, Paper A31, 16 pp.

Borum, J., 1983. The quantitative role of macrophytes, epiphytes, and phytoplankton under different nutrient conditions in Roskilde Fjord, Denmark. In: Proceedings of the International Symposium on Aquatic Macrophytes. Faculty of Science, Nijmegen, Netherlands, pp. 35–40.

Bos, A.R., Van Katwijk, M.M., 2005. Re-introduction of eelgrass (*Zostera marina*) in the western Wadden Sea (2002–2005). Final report, Radboud University Nijmegen, The Netherlands, 67 pp. (in Dutch).

BREC, 2000. BREC Comment on the POB Draft Impact Study – Fisherman's Island Extension. Brisbane Region Environment Council (BREC), Morningside Qld., October, 2000.

Brown-Peterson, N.J., Peterson, M.S., Rydene, D.A., Eames, R.W., 1993. Fish assemblages in natural versus well-established recolonized seagrass meadows. Estuaries 16 (2), 177–189.

Bulthuis, D.A., 1983. Effects of in situ light reduction on density and growth of the seagrass *Heterozostera tasmanica* (Martens ex Aschers.) den Hartog in Western Port, Victoria, Australia. Journal of Experimental Marine Biology and Ecology 67, 91–103.

Bulthuis, D.A., Woelkerling, W.J., 1983. Effects of in situ light reduction on density and growth of the seagrass *Heterozostera tasmanica* (Martens ex Aschers.) den Hartog in Western Port, Victoria, Australia. Journal of Experimental Marine Biology and Ecology 67, 91–103.

Burkholder, P.R., Doheny, T.E., 1968. The biology of eelgrass. Contribution No. 1227 from the Lamont Geological Observatory, Palisades, New York, 120 pp.

Caldwell, J.W., 1985. Effects of elevated turbidity and nutrients on the net production of a tropical seagrass community. Ph.D thesis, University of Florida, Gainesville FL, USA, 146 pp.

Campbell, S.J., McKenzie, L.J., 2004. Flood related loss and recovery of intertidal seagrass meadows in southern Queensland, Australia. Estuarine Coastal and Shelf Science 60, 477–490.

Carruthers, T.J.B., Walker, D.I., Kendrick, G.A., 1999. Abundance of *Ruppia megacarpa* mason in a seasonally variable estuary. Estuarine Coastal and Shelf Science 48, 497–509.

Chesire, A.C., Miller, D.J., Murray-Jones, S., Scriven, L., Sandercock, R., 2002. The Section Bank: ecological communities and strategies for the minimization of dredging impacts. A report to the Office for Coast and Marine National Parks and Wildlife, South Australia, Department for Environment and Heritage. SARDI Aquatic Sciences, West Beach.

Clarke, S.M., 1987. Sediment-seagrass dynamics in Holdfast Bay: summary. Safish 11, 4–10.

Clarke, S.M., Kirkman, H., 1989. Seagrass dynamics. In: Larkum, A.W.D., McComb, A.J., Shepherd, S.A. (Eds.), Biology of Seagrasses. A Treatise on the Biology of Seagrasses with Special Reference to the Australian Region, Aquatic Plant Studies 2. Elsevier, Amsterdam, pp. 304–345.

Coles, R., McKenzie, L., 2004. Trigger points and achieving targets for managers. Paper presented at a workshop session on management issues during the ISBW-6 Workshop, Seagrass 2004 Conference, Townsville, 24 September–1 October 2004.

Coles, R., McKenzie, L., Campbell, S., 2003. The seagrasses of Eastern Australia. In: E.P. Green, F.T. Short (Eds.) World Atlas of Seagrasses, Prepared by the UNEP World Conservation Monitoring Centre. University of California Press, Berkeley, USA, pp. 119–133.

Congdon, R.A., McComb, A.J., 1979. Productivity of *Ruppia*: seasonal changes and dependence on light in an Australian Estuary. Aquatic Botany 6, 121–132.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neall, R.V., Paruelo, J., Raskin, R.G., Sutton, P., Van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.

Czerny, A.B., Dunton, K.H., 1995. The effects of in situ light reduction on the growth of two subtropical seagrasses, *Thalassia testudinum* and *Halodule wrightii*. Estuaries 18, 418–427.

Dalla Via, J., Sturmbauer, C., Schonweger, G., Sotz, E., Mathekowitsch, S., Stifter, M., Rieger, R., 1998. Light gradients and meadow structure in *Posidonia oceanica*: ecomorphological and functional correlates. Marine Ecology Progress Series 163, 267–278.

Da Silva, J.F., Duck, R.W., Catarino, J.B., 2004. Seagrasses and sediment response to changing physical forcing in a coastal lagoon. Hydrology and Earth System Sciences 8 (2), 151–159.

Davis, R.C., Short, F.T., 1997. Restoring eelgrass, *Zostera marina* L., habitat using a new transplanting technique: the horizontal rhizome method. Aquatic Botany 59, 1–15.

Davis, R.C., Reel, J.T., Short, F.T., Montoya, D., 2002. Costs and success of large scale eelgrass plantings in New England. Paper presented at the Conference on Seagrass Restoration: Success and Failure and the Cost of Both. Mote Marine Laboratory, March, 2002.

De Falco, G., Murru, E., Baroli, M., Piergallini, G., Cancemi, G., 2000. Photo-aerial image processing and sediment analysis as indicators of environmental impact on *Posidonia oceanica* in the Mediterranean Sea. Biologia Marina Mediterranea 7 (2), 349–352.

De Jong, R., Van Gelderen, P., Lindo, M., Fernandez, J., 2005. Dubai's extreme reclamations. Paper presented at the CEDA Dredging Days 2005 Conference, 2–4 November 2005, Rotterdam, The Netherlands.

Dennison, W.C., 1987. Effects of light on seagrass photosynthesis, growth and depth distribution. Aquatic Botany 27, 15–26.

Dennison, W.C., 1991. Photosynthetic and growth responses of tropical and temperate seagrasses in relation to secchi depth, light attenuation and daily light period. In: W.J. Kenworthy, D.E. Haunert (Eds.), The Light Requirements of Seagrasses: Proceedings of a Workshop to Examine the Capability of Water Quality Criteria, Standards and Monitoring Programs to Protect Seagrasses, pp. 133–144. NOAA Technical Memorandum NMFS-SEFC-287.

Dennison, W.C., Orth, R.J., Moore, K.A., Stevenson, J.C., Carter, V., Kollar, S., Bergstrom, P.W., Batiuk, R.A., 1993. Assessing water quality with submerged aquatic vegetation. BioScience 43, 86–94.

Dial Cordy and Associates, 2002. Miami Harbor GRR Study – Draft Environmental Impact Statement. Mitigation Plan. Prepared for US Army Corps of Engineers. Jacksonville Beach, FL, July 2002, 25 pp.

Di Carlo, G., Badalamenti, F., Passalacqua, C., 2004. The use of reconstructive methods in combination with 'beyond BACI' designs: the case study of Capo Feto (SW Sicily, Italy). Rapport Commission Internationale pour la Mer Mediterranee 37, 514.

Di Carlo, G., Badalamenti, F., Jensen, A.C., Koch, E.W., Riggio, S., 2005. Colonization process of vegetative fragments of *Posidonia oceanica* (L.) Delile on rubble mounds. Marine Biology 147 (6), 1261–1270.

Dixon, L.K., 2000. Establishing light requirements for the seagrass *Thalassia testudinum*: an example from Tampa Bay, Florida. In: Bortone, S.A. (Ed.), Seagrasses: Monitoring, Ecology, Physiology and Management. CRC Press, pp. 9–31.

Drew, E.A., 1978. Factors affecting photosynthesis and its seasonal variation in the seagrasses *Cymodocea nodosa* (Ucria) Aschers, and *Posidonia oceanica* (L.) Delile in the Mediterranean. Journal of Experimental Marine Biology and Ecology 31, 173–194.

Duarte, C.M., 1991. Seagrass depth limits. Aquatic Botany 40, 363–377.

Duarte, C.M., 2002. The future of seagrass meadows. Environmental Conservation 29 (2), 192–206.

Duarte, C.M., Terrados, J., Agawin, N.S.R., Bach, S., Kenworthy, W.J., 1997. Response of a mixed Philippine seagrass meadow to experimental burial. Marine Ecology Progress Series 147, 285–294.

Dunton, K.H., 1994. Seasonal growth and biomass of the subtropical seagrass *Halodule wrightii* Aschers. in relation to continuous measurements of underwater irradiance. Marine Biology 120, 479–489.

Dunton, K.H., Tomasko, D.A., 1991. Seasonal variation in the photosynthetic performance of *Halodule wrightii* measured in situ in Laguna Madre, Texas. In: Kenworthy, W.J., Haunert, D.E., (Eds.), The Light Requirements of Seagrasses: Proceedings of a Workshop to Examine the Capability of Water Quality Criteria, Standards and Monitoring Programmes to Protect Seagrasses. NOAA Technical Memorandum, NMFSSEFC287, pp. 71–78.

Edmunds, M., Hart, S., Ingwersen, C., Robinson, J., Ngo, A.T., 2004. Port Phillip Bay Channel Deepening Project. Environmental Effects Statement – Marine Ecology Specialist Studies. Vol. 16: Seagrass Impact and Risk Assessment. Report to Port of Melbourne Corporation and Parsons Brinckerhoff. Australian Marine Ecology report No. 174, Melbourne, 80 pp.

EEA, 2005. Priority issues in the Mediterranean environment. UNEP, European Environment Agency (EEA), Copenhagen. EEA report No. 5/2005, 90 pp.

Environmental Affairs Consultants, 2005. Third annual progress and seagrass mitigation credit/success confirmation report. Report prepared for Manatee County Port Authority. Environmental Affairs Consultants Inc., Palmetto FL, March 2005, 63 pp.

EPA, 1998. Changes in seagrass coverage and links to water quality off the Adelaide Metropolitan coastline. Environment Protection Agency, Department for Environment, Heritage and Aboriginal Affairs, Adelaide (Australia). Technical document, September 1998, 27 pp.

EPA, 2001. Guidelines for Dredging. Best Practice Environmental Management. Environmental Protection Agency (EPA), Southbank, Victoria (Australia), publication No. 691, 110 pp.

Erftemeijer, P.L.A., 2002. Evaluation of ecological impacts of dredging activities in the Ems estuary for the deepening of an existing 42 in. gas pipeline for the NV Nederlandse Gasunie. WL | Delft Hydraulics, technical report No. Z3401, 78 pp (in Dutch).

Erftemeijer, P.L.A., Wijsman, J., 2004. Monitoring of waterbirds, eelgrass meadows and mussel beds on the Hond-Paap tidal flat during dredging activities for the deepening of the 'Eemszinker' (gas pipeline) in 2003. WL | Delft Hydraulics, technical report No. Z3540, 99 pp (in Dutch).

Erftemeijer, P.L.A., Villars, N., Gerritsen, H., Tatman, S., 2002. Feasibility study: application of remote sensing and DMI for monitoring environmental effects of dredging. WL | Delft Hydraulics, technical report No. Z3419, 38 pp.

Eurosion, 2004. Living with coastal erosion in Europe: sediment and space for sustainability. Guidelines for incorporating coastal erosion issues into Environmental Assessment (EA) procedures. Final Report to the European Commission (Service contract B4-3301/2001/329175/MAR/B3). National Institute for Coastal and Marine Management (and partners), The Netherlands, May 2004.

FFWCC, 2001. Minimizing and mitigating impacts to seagrass. Comments by the Florida Fish and Wildlife Conservation Commission at an Informal Discussion Session during ERF 2001, Florida, 7 November 2001.

Filho, G.M.A., Creed, J.C., Andrade, L.R., Pfeiffer, W.C., 2004. Metal accumulation by *Halodule wrightii* populations. Aquatic Botany 80, 241–251.

Fitzpatrick, J., Kirkman, H., 1995. Effects of prolonged shading on growth and survival of seagrass *Posidonia australis* in Jervis Bay, New South Wales, Australia. Marine Ecology Progress Series 127, 279–289.

Fletcher, S.W., Fletcher, W.W., 1995. Factors affecting changes in seagrass distribution and diversity patterns in the Indian River Lagoon complex between 1940 and 1992. Bulletin of Marine Science 57 (1), 49–58.

Fong, T.C.W., 2000. Habitat preservation or transplantation: which is better for Hong Kong seagrass conservation? Porcupine! 20, 12–14

Fong, T.C.W., 2001. Problems and prospects of seagrass conservation and management in Hong Kong and China. Paper presented at the International Symposium on Protection and Management of Coastal Marine Ecosystem. Bangkok, Thailand, 12–13 December 2000, 5 pp.

Fonseca, M.S., 1989. Sediment stabilisation by *Halophila decipiens* in comparison to other seagrasses. Estuarine Coastal and Shelf Science 17, 367–380.

Fonseca, M.S., 2002. Evaluating the effect of offshore sandbars on seagrass recovery and restoration in Tampa Bay through ecological forecasting and hindcasting of exposure to waves. Final report prepared for the Tampa Bay Estuary Program. National Oceanic and Atmospheric Administration (NOAA), Beaufort, North Carolina (USA), 50 pp.

Fonseca, M.S., Fisher, J.S., 1986. A comparison of canopy friction and sediment movement between four species of seagrass with reference to their ecology and restoration. Marine Ecology Progress Series 29, 15–22.

Fonseca, M.S., Kenworthy, W.J., Julius, B.E., Shutler, S., Fluke, S., 2002. Seagrasses. In: Perrow, M.R., Davey, A.J. (Eds.), Handbook of Ecological Restoration, vol. 2. Cambridge University Press, New York, NY, USA, pp. 149–170.

Fourqurean, J.W., Durako, M.D., Hall, M.O., Hefty, L.E., 1999. Seagrass distribution in south Florida: a multi-agency coordinated monitoring program. In: Porter, J.W., Porter, K.G. (Eds.), Linkages between ecosystems in the South Florida hydroscape: The river of grass continues. CRC Press, Boca Raton, Florida.

Fourqurean, J.W., Zieman, J.C., 1991. Photosynthesis, respiration and whole plant carbon budget of the seagrass *Thalassia tesudinum*. Marine Ecology Progress Series 69, 161–170.

Frederiksen, M., Krause-Jensen, D., Holmer, M., Laursen, J.S., 2004. Long-term changes in area distribution of eelgrass (*Zostera marina*) in Danish coastal waters. Aquatic Botany 78, 167–181.

Gaby, R., Langley, S., Keough, R.F., 1986. Port of Miami seagrass restoration: analysis of management and economics of a large scale dredge mitigation project. In: J.H. Volbeda, V.L. van Dam, N. Oosterbaan (Eds.) Proceedings of the XIth World Dredging Congress, Brighton, UK, 4–7 March 1986, pp. 550–561. Central Dredging Association, Delft.

Gambi, M.C., Dappiano, M. Lorenti, M., Iacono, B., Flagella, S., Buia, M.C., 2005. Chronicle of a death foretold. Features of a *Posidonia oceanica* bed impacted by sand extraction. In: E. Özhan (Ed.) Proceedings of the Seventh International Conference on the Mediterranean Coastal Environment, MEDCOAST 05, Kusadasi, Turkey, 25–29 October 2005, pp. 441–450.

GHD, 2005. Port of Weipa Capital Dredging. Draft Environmental Impact Statement. GHD Pty. Ltd, Brisbane, Australia 143 pp.

Giesen, W.B.J.T., Van Katwijk, M.M., Den Hartog, C., 1990. Eelgrass condition and turbidity in the Dutch Wadden Sea. Aquatic Botany 37, 71–85.

Gordon, D.M., Grey, K.A., Chase, S.C., Simpson, C.J., 1994. Changes to the structure and productivity of a *Posidonia sinuosa* meadow during and after imposed shading. Aquatic Botany 47, 265–275.

Gordon, D.M., Collins, P., Baxter, I.N., LeProvost, I., 1996. Regression of seagrass meadows, changes in seabed profiles and seagrass composition at dredged and undredged sites in the Owen Anchorage region of South-western Australia. In J. Kuo, R.C. Phillips, D.I. Walker, H. Kirkman (Eds.) Seagrass Biology: Proceedings of an International Workshop, Rottnest Island, Western Australia, 25–29 January 1996, pp. 323–332.

Green, E.P., Short, F.T., 2003. World Atlas of Seagrasses. Prepared by the UNEP World Conservation Monitoring Centre, University of California Press, Berkeley, USA, 298 pp.

Grice, A.M., Loneragan, N.R., Dennison, W.C., 1996. Light intensity and the interactions between physiology, morphology and stable isotope ratios in five species of seagrass. Journal of Experimental Marine Biology and Ecology 195, 91–110.

Halun, Z., Terrados, J., Borum, J., Kamp-Nielsen, L., Duarte, C.M., Fortes, M.D., 2002. Experimental evaluation of the effects of siltation-derived changes in sediment conditions on the Philippine seagrass *Cymodocea rotundata*. Journal of Experimental Marine Biology and Ecology 279, 73–87.

Hart, S., Edmunds, M., Elias, J., Power, B., 2004. Port Phillip Bay Channel Deepening Project. Environmental Effects Statement – Marine Ecology Specialist Studies. Vol. 5: Seagrass and Sediment Biota. Report to Port of Melbourne Corporation and Parsons Brinckerhoff. Australian Marine Ecology report No. 162, Melbourne, 119 pp.

Hemminga, M.A., Duarte, C.M., 2000. Seagrass Ecology. Springer, Cambridge (UK), 298 pp.

Iverson, R.L., Bittaker, H.F., 1986. Seagrass distribution and abundance in eastern Gulf of Mexico coastal waters. Estuarine, Coastal and Shelf Science 22, 577–602.

Jackson, E.L., Rowden, A.A., Attrill, M.J., Bossey, S.J., Jones, M.B., 2001. The importance of seagrass beds as a habitat for fishery species. Oceanography and Marine Biology – An Annual Review 39, 269–303.

Jensen, A., Lyngby, J.E., 1999. Environmental management and monitoring at the Öresund Fixed Link. Terra et Aqua 74, 10–20.

Jensen, A., Mogensen, B., 2000. Effects, ecology and economy. Environmental aspects of dredging - Guide No. 6. International Association of Dredging Companies (IADC) and Central Dredging Association (CEDA), 119 pp.

Johansson, J.0.R., Lewis, R.R., 1992. Recent improvements of water quality and biological indicators in Hillsborough Bay, a highly impacted subdivision of Tampa Bay, Florida, USA. Science of the Total Environment 1992 (Suppl), 1199–1215.

Kenyon, R., Burridge, C., Poiner, I., Hopkins, E., 1999. Impact of the McArthur River Project Mine Transhipment Facility on the marine environment. CSIRO Marine Research, final report to McArthur River Mining Pty. Ltd., 139 pp.

Kenworthy, W.J., Fonseca, M.S., 1996. Light requirements of seagrasses *Halodule wrightii* and *Syringodium filiforme* derived from the relationship between light attenuation and maximum depth distribution. Estuaries 19, 740–750.

Kirkman, H., 1978. Decline of seagrass in northern areas of Moreton Bay, Queensland. Aquatic Botany 5, 63–76.

Kirsch, K.D., Barry, K.A., Fonseca, M.S., Whitfield, P.E., Meehan, S.R., Kenworthy, W.J., Julius, B.E., 2005. The mini-312 program – an expedited damage assessment and restoration process for seagrasses in the Florida Keys National Marine Sanctuary. Journal of Coastal Research 40 (Special Issue), 109–119.

Koch, E.W., 2001. Beyond light: physical, geological and geochemical parameters as possible submerged aquatic vegetation habitat requirements. Estuaries 24 (1), 1–17.

Koch, E.W., Beer, S., 1996. Tides, light and the distribution of *Zostera marina* in Long Island Sound, USA. Aquatic Botany 53, 97–107.

Krause-Jensen, D., Middelboe, A.L., Christensen, P.B., Sand-Jensen, K., 2001. Eelgrass (*Zostera marina*) as an indicator of environmental quality. Paper presented at the Öresund Fixed Link Symposium, Stockholm University, November 27–28, 2001. Book of abstracts (oral presentations), p. 144.

Larkum, A.W.D., West, R.J., 1990. Long-term changes of seagrass meadows in Botany Bay, Australia. Aquatic Botany 37 (1), 55–70.

Lee, S.Y., 1997. Annual cycle of biomass of a threatened population of the intertidal seagrass *Zostera japonica* in Hong Kong. Marine Biology 129 (1), 183–193.

Lee, K., Dunton, K.H., 1997. Effects of in situ light reduction on the maintenance, growth and partitioning of carbon resources in *Thalassia testudinum* Banks ex Konig. Journal of Experimental Marine Biology and Ecology 210, 53–73.

Lewis, R.R., 1976. Impact of dredging in the Tampa Bay estuary, 1876–1976. In: Pruitt, E.L. (Ed.), Time-stressed Coastal Environments: Assessment and Future Action. The Coastal Society, Arlington, Virginia (USA), pp. 31–55.

Lewis, R.R., 1987. The restoration and creation of seagrass meadows in the southeastern United States. In: M.J. Durako, R.C. Phillips, R.R. Lewis (Eds.) Proceedings of the Symposium on Subtropical Seagrasses of the Southeastern United States, pp. 153–173. Florida Department of Natural Resources – Marine Research Publications No. 42, St. Petersburg, Florida.

Lewis, R.R., Durako, M.J., Moffler, M.D., Phillips, R.C., 1985. Seagrass meadows of Tampa Bay. In: Treat, S.F., Simon, J.L., Lewis, R.R. III, Whitman, R.L. Jr. (Eds.), Proceedings, Tampa Bay Area Scientific Information Symposium (May 1982). Burgess Publishing Co., Minneapolis, pp. 210–246.

Lewis, R.R., Clark, P.A., Fehring, W.K., Greening, H.S., Johansson, R.O., Paul, R.T., 1998. The rehabilitation of the Tampa Bay estuary, Florida, USA, as an example of successful integrated coastal management. Marine Pollution Bulletin 37 (8–12), 468–473.

Lewis, R.R., Marshall, M.J., Bloom, S.A., Hodgson, A.B., Flynn, L.F., 2006. Evaluation of the success of seagrass mitigation at Port Manatee, Tampa Bay, Florida. Proceedings of the Conference on Seagrass Restoration: Success and Failure and the Cost of Both. Mote Marine Laboratory, March 11–12, 2002, pp. 19–40.

Long, B.G., Dennis, D.M., Skewes, T.D., Poiner, I.R., 1996. Detecting an environmental impact of dredging on seagrass beds with a BACIR sampling design. Aquatic Botany 53, 235–243.

Longstaff, B.J., Dennison, W.C., 1999. Seagrass survival during pulsed turbidity events: the effects of light deprivation on the seagrasses *Halodule pinifolia* and *Halophila ovalis*. Aquatic Botany 65, 105–121.

Longstaff, B.J., Lonerragan, N.R., O'Donohue, M.J., Dennison, W.C., 1999. Effects of light deprivation on the survival and recovery of the seagrass *Halophila ovalis* (R. Br.) Hook. Journal of Experimental Marine Biology and Ecology 234, 1–27.

Lord & Associates, 2000. Long-term shells and dredging, Owen Anchorage. Environmental review and management programme. Technical report prepared for the Environmental Protection Authority. D.A. Lord and Associates Pty. Ltd. Report No. 96/032/4, November 2000, 145 pp.

Lord, D., Paling, E., Gordon, D., 1999. Review of Australian rehabilitation and restoration programs. In: Seagrass in Australia – Strategic Review and Development of an R&D Plan. CSIRO Marine Research, Collingwood (Australia), pp. 65–115.

MacArthur Report, 1997. Death of the Indian River Lagoon? A Report to the John D. and Catherine T. MacArthur Foundation. August 1997.

MacInnis-Ng, C., 2003. In situ stress monitoring of anthropogenic impacts on *Zostera capricorni*. Ph.D. thesis, Department of Environmental Sciences, University of Technology, Sydney.

Manzanera, M., Perez, M., Romero, J., 1995. Seagrass mortality due to oversedimentation: an experimental approach. In: Proceedings of the Second International Conference on the Mediterranean Coastal Environment, MEDCOAST 95, October 24–27 1995, Taragona, Spain.

Marba, N., Duarte, C.M., 1994. Growth response of the seagrass *Cymodocea nodosa* to experimental burial and erosion. Marine Ecology Progress Series 107, 307–311.

Merkel, K.W., 2003. Eelgrass habitat surveys for the Emeryville Flats and Clipper Cove, Yerba Buena Island (October 1999 through October 2002). San Francisco – Oakland Bay Bride, East Span Seismic Safety Project. Merkel and Associates, Inc., technical report M&A 99-104-10A, 27 pp.

Mills, K.E., Fonseca, M.S., 2003. Mortality and productivity of eelgrass *Zostera marina* under conditions of experimental burial with two sediment types. Marine Ecology Progress Series 255, 127–134.

Moberg, F., Rönnbäck, P., 2003. Ecosystem services of the tropical seascape: interactions, substitutions and restoration. Ocean and Shoreline Management 46, 27–46.

Montagna, P.A., Holt, S.A., Ritter, C., Herzka, S., Binney, K.F., Dunton, K.H., 1998. Characterization of anthropogenic and natural disturbance on vegetated and unvegetated bay bottom habitats in the Corpus Christi Bay National Estuary Program study area. Vol. I: Literature review. University of Texas, Publication CCBNEP-25A, May 1998.

Moore, K.A. 1991. Field studies of the effects of variable water quality on temperate seagrass growth and survival. In: Kenworthy, W.J., Haunert, D.E., (Eds.), The Light Requirements of Seagrass. NOAA Technical Memorandum NMFSSEFC287, pp. 42–57.

Moore, K.A., Wetzel, R.L., Orth, R.J., 1997. Seasonal pulses of turbidity and their relations to eelgrass (*Zostera marina* L.) survival in an estuary. Journal of Experimental Marine Biology and Ecology 215, 115–134.

Newell, R.C., Seiderer, L.J., Hitchcock, D.R., 1998. The impact of dredging works in coastal waters: a review of the sensitivity to disturbance and subsequent recovery of biological resources on the seabed. Oceanography and Marine Biology – An Annual Review 36, 127–178.

Ochieng, C.A., Short, F.T., Walker, D.I., 2004. Early flowering, architecture and photosynthesis of perennial eelgrass in light manipulation experiments. Paper presented at the Seagrass 2004 Conference, Townsville, 24 September–1 October 2004.

Olsen, E., 2005. Evaluating the sustainability of offshore dredging and coastal zone governance. B.Sc. thesis, University of East Anglia, January 2005.

Onuf, C.P., 1991. Light requirements of *Halodule wrightii, Syringodium filiforme*, and *Halophila engelmannii* in a heterogeneous and variable environment inferred from long-term monitoring. In: Kenworthy, W.J., Haunert, D.E. (Eds.), The Light Requirements of Seagrasses: Proceedings of a Workshop to Examine the Capability of Water Quality Criteria, Standards and Monitoring Programmes to Protect Seagrasses. NOAA Technical Memorandum, NMFSSEFC287, pp. 95–105.

Onuf, C.P., 1994. Seagrasses, dredging and light in Laguna Madre, Texas, USA. Estuarine Coastal and Shelf Science 39, 75–91.

Onuf, C.P., 1996. Seagrass responses to long-term light reduction by brown tide in upper Laguna Madre, Texas: distribution and biomass patterns. Marine Ecology Progress Series 138, 219–231.

Onuf, C.P., 2000. Seagrass responses to and recovery (?) from seven years of brown tide. Pacific Conservation Biology 5, 306–313.

Orpin, A.R., Ridd, P.V., Thomas, S., Anthony, K.R.N., Marshall, P., Olivier, J., 2004. Natural variability and weather forecasts in risk management of anthropogenic sediment discharge near sensitive environments. Marine Pollution Bulletin 49, 602–612.

Orth, R.J., Fishman, J.R., Wilcox, D.J., Moore, K.A., 2002. Identification and management of fishing gear impacts in a recovering seagrass system in the coastal bays of Delmarva Peninsula, USA. Journal of Coastal Research, SI 37, 111–129.

OSPAR, 1998. OSPAR Guidelines for the Management of Dredged Material. Ministerial Meeting of the OSPAR Commission, Sintra 23–23 July 1998; Summary Record OSPAR 98/14/1-E, Annex 43 (Reference Number 1998-20), 32 pp.

OSPAR, 2004. Environmental impacts to marine species and habitats of dredging for navigational purposes. OSPAR Commission, Biodiversity Series, 22 pp.

Ostenfeld, C.H. 1908. On the ecology and distribution of the grasswreck (*Zostera marina*) in Danish waters. Report of the Danish Biological Station, Copenhagen, Denmark.

Paling, E.I., Van Keulen, M., Wheeler, K., Phillips, J., Dyhrberg, R., 2001. Mechanical transplantation in Western Australia. Ecological Engineering 16, 331–339.

Pasqualini, V., Pergent-Martini, C., Pergent, G., 1999. Environmental impact identification along the Corsican coast (Mediterranean sea) using image processing. Aquatic Botany 65, 311–320.

Peňa, C., 2005. The Underwater Gardeners. Dredging and Port Construction (DPC), September 1995, pp. 32–34.

Penn, N., 1981. The environmental consequences and management of coral sand dredging from seagrass beds in the Suva region, Fiji Islands. Bulletin of Marine Science 31 (3), 814.

Pennekamp, J.G.S., Epskamp, R.J.C., Rosenbrand, W.F., Mullie, A., Wessel, G.L., Arts, T., Deibel, I.K., 1996. Turbidity caused by dredging: viewed in perspective. Terra et Aqua 64, 10–17.

Peralta, G., Perez-Lorens, J.L., Hernandez, I., Vergara, J.J., 2002. Effects of light availability on growth, architecture and nutrient content of the seagrass *Zostera noltii* Hornem. Journal of Experimental Marine Biology and Ecology 269, 9–26.

POB, 2000. Draft Environmental Impact Assessment Study – Fisherman's Island Extension. Port of Brisbane Corporation, Brisbane, Queensland.

Port of Melbourne Corporation, 2004. Port of Melbourne Corporation Channel Deepening Project Draft Environmental management Plan. Chapter 5: Environmental Monitoring Program, pp. 5.1–5.33.

Preen, A., 1995. Impacts of dugong foraging on seagrass habitats: observational and experimental evidence for cultivation grazing. Marine Ecology Progress Series 124, 201–213.

Preen, A.R., Lee Long, W.J., Coles, R.G., 1995. Flood and cyclone related loss, and partial recovery, of more than 1000 km^2 of seagrasses in Hervey Bay, Queensland, Australia. Aquatic Botany 52, 3–17.

Pringle, A.W., 1989. The history of dredging in Cleveland Bay, Queensland and its effect on sediment movement and on the growth of mangroves, corals and seagrass. Great Barrier Reef Marine Park Authority, Townsville, 174.

Pulich Jr., W.M., White, W.A., 1991. Decline of submerged vegetation in the Galveston Bay system: chronology and relationship to physical processes. Journal of Coastal Research 4, 1125–1138.

Purkis, S.J., Riegl, B., 2005. Spatial and temporal dynamics of Arabian Gulf coral assemblages quantified from remote-sensing and in situ monitoring. Marine Ecology Progress Series 287, 99–113.

Quammen, M.L., Onuf, C.P., 1993. Laguna Madre – seagrass changes continue decades after salinity reduction. Estuaries 16 (2), 302–310.

Rasheed, M.A., 1999. Recovery of experimentally created gaps within a tropical *Zostera capricorni* (Aschers.) seagrass meadow, Queensland Australia. Journal of Experimental Marine Biology and Ecology 235, 183–200.

Rasheed, M.A., Roelofs, A.J., Thomas, R., Coles, R.G., 2001. Port of Karumba Seagrass Monitoring – First Six Years (1994–2000). EcoPorts Monograph Series No. 20, Ports Corporation of Queensland, 38 pp.

Ruiz, J.M., Romero, J., 2003. Effects of disturbances caused by coastal constructions on spatial structure, growth dynamics and photosynthesis of the seagrass *Posidonia oceanica*. Marine Pollution Bulletin 46, 153–1523.

Sabol, B., Shafer, D., 2005. Dredging effects on seagrasses: case studies from New England and Florida. In: Proceedings, Western Dredging Association, Twenty-fifth Technical Conference and Thirty-seventh Annual Texas A& M Dredging Seminar, June 19–22 2005, New Orleans, Louisiana, USA. Center for Dredging Studies, CDA Report No. 507, pp. 335–346.

Sabol, B.M., Shafer, D.J., 2005. Dredging effects on seagrasses: case studies from New England and Florida. In: Proceedings of the Western Dredging Association, pp. 336–346.

Sabol, B., Shafer, D., Lord, E., 2005. Dredging effects on eelgrass (*Zostera marina*) distribution in a New England small boat harbor. US Army Corps of Engineers, Engineer Research and Development Center, Environmental Laboratory, Technical Report ERDC/EL TR-05-8, 31 pp.

Schwarz, A.M., Bjork, M., Buluda, T., Mtolera, H., Beer, S., 2000. Photosynthetic utilisation of carbon and light by two tropical seagrass species as measured in situ. Marine Biology 137, 755–761.

Scoffin, T.P., 1979. The trapping and binding of subtidal carbonate sediments by marine vegetation in Bimini Lagoon, Bahamas. Journal of Sedimentary Petrology 40, 249–273.

Shafer, D.J., 1999. The effects of dock shading on the seagrass *Halodule wrightii* in Perdido Bay, Alabama. Estuaries 22, 936–943.

Shaw, B.J., 2000. Bali: paradise sustainable? Current Issues in Tourism 3 (1), 81–85.

Shepherd, S.A., McComb, A.J., Bulthuis, D.A., Neverauskas, V., Steffensen, D.A., West, R., 1989. Decline of seagrasses. In: Larkum, A.W.D., McComb, A.J., Shepherd, S.A. (Eds.), Seagrasses: A Treatise on the Biology of Seagrasses with Special Reeference to the Australian Region. Elsevier, North Holland, pp. 346–387.

Sheridan, P., 2004. Recovery of floral and faunal communities after placement of dredged material on seagrasses in Laguna Madre, Texas. Estuarine Coastal and Shelf Science 59, 441–458.

Short, F.T., 2003. Loss and restoration of seagrass ecosystems. Paper presented at the 5th International Conference on Environmental Future (5th ICEF); 23–27 March 2003, Zurich, Switzerland.

Short, F.T., Wyllie-Echeverria, S., 1996. Natural and human induced disturbances of seagrasses. Environmental Conservation 23, 17–27.

Short, F.T., Wyllie-Echeverria, S., 2000. Global seagrass declines and effect of climate change. In: Shepperd, C.R.C. (Ed.), Seas at the Millennium: An Environmental Evaluation, vol. III. Pergamon, Elsevier, Amsterdam, pp. 10–11.

Short, F.T., Wolf, M.W., Jones, G.E., 1989. Sustaining eelgrass to manage a healthy estuary. In: Proceedings of the Sixth Symposium on Coastal and Ocean Management/ASCE, July 11–14, Charlestown SC, pp. 3689–3706.

Short, F.T., Burdick, D.M., Kaldy III, J.E., 1995. Mesocosm experiments quantify the effects of eutrophication on eelgrass, *Zostera marina*. Limnology and Oceanography 40, 740–749.

Short, F.T., Burdick, D.M., Short, C.A., Davis, R.C., Morgan, P.M., 2000. Developing success criteria for restored eelgrass, salt marsh and mud flat habitats. Ecological Engineering 15, 239–252.

SMEC, 2003. Towra Beach Nourishment. Vol. 1. Environmental Impact Statement. Prepared for the Waterways Authority and NSW National Parks and Wildlife Service, August 2003.

Smith, S.R., 1999. Impact of the construction of Kindley Field Airbase on the marine environment of Castle Harbour, Bermuda. Unpublished report to the Government of Bermuda.

Smits, J., 1998. Machines, methods and mitigation. Environmental aspects of dredging, Guide No. 4. IADC/CEDA, 80 pp.

Spalding, M., Taylor, M., Ravilious, C., Short, F., Green, E., 2003. The distribution and status of seagrasses: a global overview. In: E.P. Green, F.T. Short (Eds.) World Atlas of Seagrasses, pp. 5–26. Prepared by the UNEP World Conservation Monitoring Centre, University of California Press, Berkeley, USA.

Stern, E.M., Stickle, W.B., 1978. Effects of turbidity and suspended sediment in aquatic environments: literature review. US Army Corps of Engineers, Waterways Experiment Station, Vicksburg MS, USA. Technical report No. 0-78-21.

Sterrer, W.E., Wingate, D.B., 1981. Wetlands and marine environments. In: Hayward, S.J., Gomez, V.H., Sterrer, W.E. (Eds.), Bermuda's Delicate Balance. Bermuda National Trust, pp. 107–122.

Tatman, S., Gerritsen, H., Hesselmans, G., Dirks, W., Noorbergen, H., Dardengo, L., Kleissen, F., Van den Boogaard, H., 2005. Remote Sensing as a Tool for Scheduling and Control of Dredging (REST-COD). Inception Phase. WL | Delft Hydraulics, Technical report No. Z3460, 144 pp.

Taylor, J.L., Saloman, C.H., 1968. Some effects of hydraulic dredging and coastal development in Boca Ciega Bay, Florida. US Fish Wildlife Service. Fishery Bulletin 67 (2), 213–241.

Terrados, J., Duarte, C.M., Fortes, M.D., Borum, J., Agawin, N.S.R., Bach, S., Thampanya, U., Kamp-Nielsen, L., Kenworthy, W.J., Geertz-Hansen, O., Vermaat, J., 1998. Changes in community structure and biomass of seagrass communities along gradients of siltation in SE Asia. Estuarine Coastal and Shelf Science 46 (5), 757–768.

Thorhaug, A., Austin, C.B., 1976. Restoration of seagrasses, with economic analysis. Environmental Conservation 3 (4), 259–267.

Thorkilsen, M., Dynesen, C., 2001. An owner's view of hydroinformatics: its role in realising the bridge and tunnel construction between Denmark and Sweden. Journal of Hydroinformatics 03.2, 105–135.

Thorogood, J., Conacher, C., Fowler, R., Ross, J., 2001. Southern Bay Islands Transport Study. FRC Environmental, Wellington Point Qld. Technical report No. 01.03.01, 53 pp.

USACE, 1983. Dredging and dredged material disposal. Engineering and Design. U.S. Army Corps of Engineers, Engineer Manual EM 1110-2-5025.

USACE, 2005. Silt curtains as a dredging project management practice. ERDC TN-DOER-E21, September 2005, 18 pp.

Van Eepoel, R.P., 1969. Effects of dredging in Water Bay, St. Thomas. Caribbean Research Institute, Water Pollution Report No. 2, 11 pp.

Vermaat, J.E., Agawin, N.S.R., Fortes, M.D., Uri, J.S., 1997. The capacity of seagrasses to survive increased turbidity and siltation: the significance of growth form and light use. Ambio 25 (2), 499–504.

Vicente, V.P., Rivera, J.A., 1982. Depth limits of the seagrass *Thalassia testudinum* (Konig) in Jobos and Guayanilla Bays, Puerto Rico. Caribbean Journal of Science 17, 73–76.

Virnstein, R.W., Morris, Lj., 1996. Seagrass preservation and restoration: a diagnostic plan for the Indian River Lagoon. Technical Memorandum #14. St. Johns River Water Management District, Palatka, Fl., 43 pp.

Wakibya, J.G., 1995. The potential human-induced impacts on the Kenyan seagrasses. UNESCO Reports in Marine Science 66, 176–187.

Walker, D.I., McComb, A.J., 1992. Seagrass degradation in Australian coastal waters. Marine Pollution Bulletin 25 (5–8), 191–195.

Walker, D.I., Hillman, K.A., Kendrick, G.A., Lavery, P., 2001. Ecological significance of seagrasses: assessment for management of environmental impact in Western Australia. Ecological Engineering 16, 323–330.

Weitkamp, L., 1998. Long-term monitoring of the Navy's Manchester eelgrass bed. In: Proceedings of the 1998 Puget Sound Research Conference, pp. 382–387.

Westphalen, G., Collings, G., Wear, R., Fernandes, M., Bryars, S., Chesire, A., 2004. A review of seagrass loss on the Adelaide metropolitan coastline. Adelaide Coastal Waters Study, technical report No. 2, August 2004.

Williams, S.L., 1988. Disturbance and recovery of a deep water Caribbean seagrass bed. Marine Ecology Progress Series 42, 63–71.

Williams, S.L., Dennison, W.C., 1990. Light availability and diurnal growth of a green macroalga (*Caulerpa cupressoides*) and a seagrass (*Halophila decipiens*). Marine Biology 106, 437–443.

WMB, 2001. Moreton Bay Sand Extraction Study – Phase 1. Prepared for Moreton Bay Sand Extraction Study Steering Committee. WBM Oceanics Australia, technical report, Spring Hill Qld.

Wyllie, A., Kendrick, G., Davidson, A., Hegge, B., 1997. Changes in seagrass coverage on Success and Parmelia Banks between 1965 and 1995. Technical report prepared for Cockburn Cement Ltd. National Geographic Information Systems, December 1987.

Zainal, A.J.M., Dalby, D.H., Robinson, I.S., 1993. Monitoring marine ecological changes on the east coast of Bahrain with Landsat TM. Photogrammetric Engineering and Remote Sensing 59 (3), 415–421.