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A conservation strategy for dugongs: implications of Australian research

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Abstract. The dugong (*Dugong dugon*) is listed as vulnerable to extinction at a global scale. It has a large range that spans some forty countries and includes tropical and subtropical coastal and island waters from east Africa to Vanuatu. A significant proportion of the world's dugongs is found in northern Australian waters where most modern dugong research has been conducted. Dugongs are long-lived animals with a low reproductive rate, long generation time, and a high investment in each offspring. Population simulations indicate that even with the most optimistic combinations of life-history parameters (e.g. low natural mortality and no human-induced mortality) a dugong population is unlikely to increase by more than 5% per year. Dugongs are vulnerable to anthropogenic impacts because of their life history and their dependence on seagrasses that are restricted to coastal habitats. Even a slight reduction in adult survivorship as a result of habitat loss, disease, hunting or incidental drowning in nets can cause a chronic decline in a dugong population. The optimum management strategy is to identify areas that consistently support large numbers of dugongs and to set these aside as dugong sanctuaries in which dugong mortality is minimized and their habitat protected.

Introduction

The dugong (*Dugong dugon*) is the only herbivorous mammal that is strictly marine and is the only extant species in the Family Dugongidae. The other members of the Order Sirenia, the three species of manatee, all use fresh water to varying degrees (Reynolds and Odell 1991). The only other recent Sirenian, Steller's sea cow *Hydrodamalis gigas,* was hunted to extinction within 27 years of its discovery in the eighteenth century (Stejneger 1887).

All extant members of the Order Sirenia are listed as vulnerable to extinction (Anon. 1996*a*). Prospects for the survival of the dugong are the best, because each manatee species has a more localized distribution than the dugong (in the West Indian region, the Amazon and in West Africa respectively; Reynolds and Odell 1991). In addition, the estimates of dugong abundance in Australia (Table 1) are much greater than have been recorded or suggested for any species of manatee.

The dugong has a large range that spans some forty countries and includes tropical and subtropical coastal and island waters from east Africa to Vanuatu, between about 26° and 27° north and south of the equator (Nishiwaki and Marsh 1985). The dugong's historic distribution was broadly coincident with the tropical Indo–Pacific distribution of its food plants, the phanerogamous seagrasses of the families Potamogetonaceae and Hydrocharitaceae (Husar 1978). It is generally believed that throughout most of this region outside Australia, the dugong is represented by relict populations separated by large areas where it is close to extirpation or is already extirpated. However, the degree to which dugong numbers have dwindled, and their range fragmented, is not known. Over most of its range outside Australia and Saudi Arabia, the dugong is known only from incidental sightings, accidental drownings and the anecdotal reports of fishermen.

Extensive aerial surveys have resulted in a more comprehensive knowledge of dugong distributions in the coastal waters of Australia (Table 1) and Saudi Arabia (Preen 1989*a*). A significant proportion of the world's dugongs is found in northern Australian waters from Moreton Bay in the east to Shark Bay in the west (Marsh and Lefebvre 1994, Table 1 and Fig. 1 of this paper). Only anecdotal information about dugong distribution and abundance is available between immediately north of Exmouth Gulf, Western Australia, and the mouth of the Daly River, Northern Territory, because of a lack of dedicated aerial surveys throughout that region.

One of the World Heritage values of the Great Barrier Reef region is that it 'provides major feeding grounds for large populations of the endangered species *Dugong dugon*' (Anon. 1981). The large population of dugongs in Shark Bay has been noted as one of the natural features associated with the World Heritage listing of that bay (Anon. 1990). Australia is accepted as the dugong's stronghold (Bertram 1981).

Dedicated aerial surveys of dugong populations in Australian waters indicate that dugongs are the most abundant marine mammal in the inshore waters of northern Australia (Marsh, unpublished). Although some areas of suitable habitat have not been surveyed, the population estimates sum to approximately 85 000 dugongs (Table 1). These estimates are underestimates because the correction for the number of

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Table 1. Most recent estimates of dugong numbers in various parts of northern Australia from strip transect aerial surveys
WA, Western Australia; NT, Northern Territory; Qld, Queensland; GBR, Great Barrier Reef

Locality	Date of survey	Area km^2	Population estimate ± s.e.	Reference
Shark Bay WA	July 1994	14 906	10 529 ± 1,464	Preen *et al.* (1997)
Exmouth Gulf – Ningaloo WA	July 1994	28 746	1 974 ± 588	Preen *et al.* (1997)
Northern coast NT	Dec. 1983	28 746	13 800 ± 2 683	Bayliss (1986); Bayliss and Freeland (1989)
NT coast of Gulf of Carpentaria	Oct. 1994 Mar.–Apr. 1995	27 216	16 846 ± 3 259	Bayliss and Freeland (1989)
Gulf coast of Qld	Dec. 1997	33 026	4 266 ± 657	Marsh *et al.* (1998)
Torres Strait	Nov. 1996	30 568	27 881 ± 3 216	Marsh *et al.* (1997*a*)
GBR region north of Cape Bedford	Nov.–Dec. 1995	25 800	8 190 ± 1 172	Marsh and Corkeron (1996)
GBR region south of Cape Bedford	Nov. 1994	39 396	1 642 ± 236	Marsh *et al.* (1996)
Hervey Bay	Nov. 1994	4 371	807 ± 151	Marsh *et al.* (1996)
Moreton Bay	July 1995	1 838	503 ± 64[A]	Lanyon (unpublished)

[A]1 019 ± 166 recorded by Lanyon (unpublished) in January 1995.

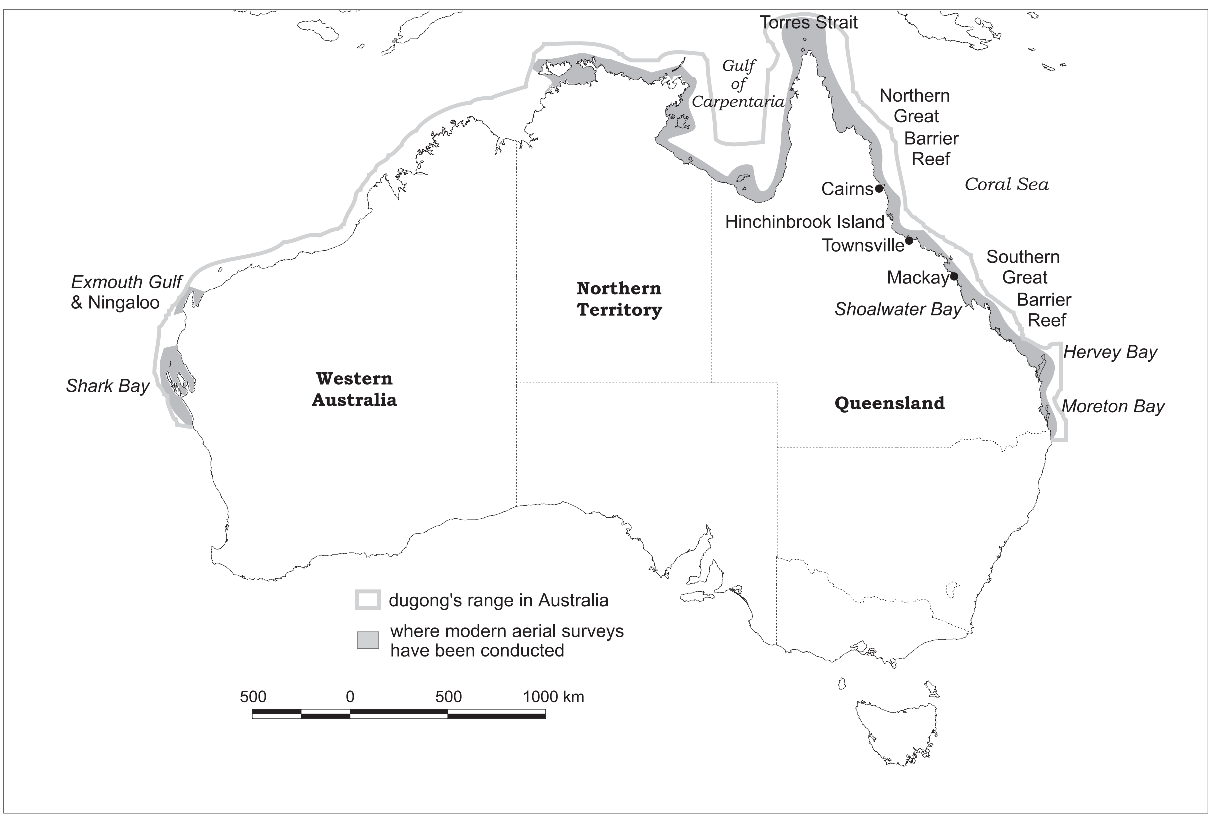

Fig. 1. Map of the range of the dugong in Australia, illustrating place names mentioned in the text.

animals that are not visible to observers owing to water turbidity is conservative (Marsh and Sinclair 1989*a*, 1989*b*).

As charismatic megafauna, the dugong is also an 'umbrella species' (a species 'with large area requirements which, when given sufficient protected area, will bring many other species under protection', Jones and Kaly 1995) for the conservation of tropical coastal environments throughout much of the Indo–West Pacific. The dugong is thus of particular conservation significance globally, nationally and regionally.

Most modern research on dugongs has been performed in Australia, particularly in Queensland. The applicability of this research to dugongs in other parts of their range is unknown. Admitting this limitation, this paper reviews the research results to provide a context for developing conservation strategies, applicable in Australia and throughout the remainder of the dugong's range. We conclude that the optimum management strategy for regions where hunting does not occur as a Native Title right is to identify areas that consistently support large numbers of dugongs and to set these aside as sanctuaries in which dugong habitat is protected and anthropogenic dugong mortality is minimized.

Biology

Life history

Almost all information on dugong life history has been obtained from the analysis of animals accidentally drowned in shark nets or killed by native hunters. The age-determination method developed for pinnipeds and toothed cetaceans was adapted for dugongs enabling their age to be estimated from the number of growth layer groups in the tusks (see Marsh 1980). Life-history parameters are summarized in Marsh (1995*a*, 1999). Dugongs are long-lived with a low reproductive rate, long generation time, and a high investment in each offspring. The oldest dugong whose tusks have been examined for age determination was estimated to be 73 years old when she died. Females do not bear their first calf until they are at least 10 and up to 17 years old. Gestation is approximately 13 months. The usual litter size is one. The calf suckles for at least 18 months, and the period between successive calvings is very variable; estimates range from three to seven years. Dugongs start eating seagrasses soon after birth, but they grow rapidly during the suckling period when they also receive milk from their mothers. Population simulations indicate that even with the most optimistic combinations of life-history parameters (e.g. low natural mortality and no human-induced mortality) a dugong population is unlikely to increase more than 5% per year (Marsh 1995*a*, 1999). This makes the dugong vulnerable to over-exploitation.

Dugong mating behaviour appears to vary spatially. Preen (1989*b*) observed mating herds in Moreton Bay, Queensland, where male dugongs violently compete for oestrous females, and similar herds have been observed in two localities in northern Queensland (Marsh 1999); several presumed males attempt to embrace the presumed female, each attempting to mate with her (see Preen 1989*b*). In contrast, resident dugongs in South Cove in Shark Bay in Western Australia exhibit mating behaviour consistent with the definition of a lek ('in a classic lek males aggregate on mutually exclusive display areas at a traditional site that lacks resources required by females, females visit this site only in order to mate' Anderson 1997). Anderson (1997) observed male dugongs defending mutually exclusive territories in which unique behaviours were displayed in order to attract females. It is not known whether lekking occurs elsewhere in the dugong's range, and its significance to the estimated 10 000 dugongs (Marsh *et al.* 1994; Preen *et al*. 1997) that live in Shark Bay is uncertain.

Diet

Dugongs are seagrass specialists, uprooting whole plants when they are accessible, but feeding only on leaves when the whole plant cannot be uprooted (Anderson 1982*a*; Marsh *et al*. 1982, 1999). However, Anderson (1998) claims that his observations in North Cove, Western Australia, suggest that dugongs selectively forage for *Halodule* rhizomes. Dugongs prefer seagrasses that are lower seral or 'pioneer' species (Preen 1995*a*, 1995*b*), especially species of the genera *Halophila* and *Halodule*. Diet selection is correlated with the chemical and structural composition of seagrass (Lanyon 1991; Aragones 1996). The most frequently selected species are lowest in fibre and highest in available nitrogen and digestibility (Lanyon 1991; Aragones 1996). Selection for the species that are highly digestible (*Halophila*) and have high nutrients (*Halodule*) means that dugongs maximize the intake of nutrients rather than bulk (Aragones 1996).

Marine algae are also eaten (Marsh *et al.* 1982), but this is believed to occur only when seagrass is scarce (Spain and Heinsohn 1973). Anderson (1989) and Preen (1995*a*) have evidence that dugongs may deliberately forage for macro-invertebrates near the southern limits of their range in both western and eastern Australia. However, examination of stomach and faecal samples (Preen 1995*a*) suggests that dugongs do not deliberately forage on macro-invertebrates in more tropical areas in Australia.

The highly specialized dietary requirements of the dugong suggest that only certain seagrass meadows may be suitable as dugong habitat (Preen 1995*b*). Preen (1995*b*), De Iongh (1996) and Aragones and Marsh (1999) suggest that grazing activities by dugongs alter the species composition of seagrass communities at a local scale. Thus, areas that support sizeable numbers of dugongs may have the capacity to provide better 'quality' food than areas that support few or no dugongs and rely only on natural turnover rates for recycling and redistribution of nutrients (Aragones and Marsh 1999).

Habitat

Dugongs frequent coastal waters. Major concentrations of dugongs tend to occur in wide shallow protected bays, wide shallow mangrove channels and in the lee of large inshore islands (Heinsohn *et al*. 1979). These areas are coincident with sizeable seagrass beds. Dugongs are also regularly observed in deeper water further offshore in areas where the continental shelf is wide, shallow and protected. In Torres

Strait between Australia and Papua New Guinea, significant numbers of dugongs are seen more than 10 km from land (Marsh and Saalfeld 1989, 1991). Marsh and Saalfeld (1989) have also sighted dugongs ~58 km from the north Queensland coast, in water up to 37 m deep. This distribution reflects that of deepwater seagrasses such as *Halophila spinulosa* (Lee Long *et al*. 1993). Dugong feeding trails have been observed at depths of up to 33 m off north-eastern Queensland (Lee Long *et al.* 1997).

There is evidence that dugongs use specialized habitats for various activities. Shallow waters, such as on tidal sandbanks (Marsh *et al*. 1984) and estuaries (Hughes and Oxley-Oxland 1971), have been reported as sites for calving. Anderson (1981) suggested that this may be a strategy to avoid sharks. The physical characteristics of South Cove in Shark Bay may make it especially suitable for the lek mating behaviour observed by Anderson (1997). At the higher latitudinal limits to their range, deeper waters may be used as a thermal refuge from cooler inshore waters (Anderson 1986; Marsh *et al*. 1990; Preen 1992).

Movements

Most movements of the more than 60 dugongs that have been tracked by means of VHF or satellite transmitters have been localised to the vicinity of seagrass beds (Marsh and Rathbun 1990; Preen 1992; De Iongh *et al.* 1998). Daily movements depend on tidal amplitutude. At localities where the tidal range is large (e.g. up to 8.5 m in Shoalwater Bay in the Mackay–Capricorn Section of the Great Barrier Reef Marine Park, Anderson and Birtles 1978) (Fig. 1), dugongs can gain access to their inshore feeding areas only when water depth is 1 m or more. In areas with low tidal amplitude such as Shark Bay (Anderson 1982*b*) or in areas where seagrass grows subtidally, daily movements are not dictated by tides.

At the high-latitude limits of their range, dugongs make seasonal movements to warmer waters. In winter in Moreton Bay, many dugongs regularly make a round trip of 15–40 km between their foraging grounds inside the bay and oceanic waters, which average up to 5°C warmer (Preen 1992). Dugongs also apparently undertake winter movements in Shark Bay to warmer waters in the westward part of that bay (Anderson 1982*b*, Marsh *et al.* 1994).

At least some individual dugongs undertake long-distance movements. An adult female moved 600 km between two sites in the Gulf of Carpentaria over about five days (Preen 1995*c*). Another male travelled between two localities, in the Central Section of the Great Barrier Reef, a straight-line distance of 140 km, three times in six weeks (Marsh and Rathbun 1990). Of the ten dugongs fitted with satellite transmitters in Shoalwater Bay (Fig. 1) by Preen (personal communication 1996), four made substantial trips out of that bay. Two made return trips: one 100 m north to Clairview, the other 220 km north to Hay Point near Mackay. Two other animals journeyed 400 km south to Hervey Bay where their transmitters came off. Thirteen dugongs were tracked between the Townsville and Hinchinbrook Island region. Twelve trips were made of more than 30 km beyond the area regularly used by these animals, six trips of more than 100 km and one trip of more than 500 km (Preen 1999). Most of these movements were return trips.

The capacity of dugongs to undertake long-distance movements indicates that the management of dugongs is an international issue in areas such as Torres Strait.

Genetic population structure

Molecular techniques have been used to investigate the genetic population structure of dugongs (Tikel 1998). Results based on mitochondrial DNA suggest that the geographical range of the South-East Asian haplotypes does not overlap with that of Australian haplotypes, suggesting that there is no genetic exchange between Australia and Asia. Genetic diversity of dugongs is high particularly in Australian waters. The genetic structure of dugong populations around the Australian coast appears to have been influenced by the former Torres Strait land bridge that once connected Australia to Papua New Guinea, even though this could not have acted as a barrier to dugong movements for 6000 years (Tikel 1998). This breeding pattern conforms with an 'isolation by distance' model; individuals are more likely to breed with others in a neighbouring bay than with dugongs some distance away. This conclusion is supported by morphometric analysis demonstrating that the skull shape of dugongs from the Wellesley Islands area is significantly different from that of dugongs from Townsville (Spain and Marsh 1981).

Tikel's (1998) studies suggest that, if dugongs disappear from an area, it is unlikely to be recolonized quickly (in a management timeframe) despite the dugong's capacity for long-distance movements of hundreds of kilometres in a few days (Marsh and Rathbun 1990; Preen 1999). These results indicate the importance of maintaining numbers throughout the dugong's range including along sections of coast where densities are low. However, although mitochondrial DNA evolves quickly and is considered a good index of population structure, it is transmitted only in the female lineage and can only be used to estimate female-mediated gene flow. In mammals, male-mediated gene flow is often markedly greater than female-mediated flow. To test for this in dugongs, a nuclear marker, or markers, must be used to make a more complete assessment of the genetic population structure.

Threatening processes

General

Dugongs are vulnerable to anthropogenic influences because of their life history and their dependence on seagrasses that are restricted to coastal habitats, which are often under pressure from human activities. The rate of population change is most sensitive to changes in adult survivorship.

Even a slight reduction in adult survivorship as a result of habitat loss, disease, hunting or incidental drowning in nets, can cause a chronic decline in a dugong population. As explained above, Marsh (1995*a*, 1999) suggested that the maximum rate of increase under optimum conditions could not exceed 5% per year even when natural mortality is low (<5% per year). The sustainable harvest is likely to be in the order of 2% of the female population per year. The sustainable harvest rate will be lower in areas where the pre-reproductive period and/or calving interval are lengthened by food shortage (Marsh 1999). Dugongs may be short of food for several reasons including habitat loss, seagrass dieback, decline in the nutrient quality of available seagrass or a reduction in the time available for feeding due to boat traffic.

Habitat loss and degradation

Seagrass ecosystems are very sensitive to human influence (Fonseca 1987; Shepherd *et al*. 1989; Poiner and Peterkin 1996). Seagrass beds may be destroyed directly by mining and trawling (Silas and Bastion-Fernando 1985), or lost through the effects of disturbances such as dredging, inland and coastal clearing, and land reclamation. These activities cause increases in sedimentation and turbidity which, in turn, lead to degradation through smothering and lack of light. Other threats include herbicide runoff, and sewage, detergents, heavy metals, hypersaline water from desalination plants and other waste products.

Most losses, both natural and anthropogenic, are attributed to reduced light intensity due to sedimentation and/or increased epiphytic growth caused by nutrient enrichment. In some cases, factors such as poor catchment management and sediment instability interact to make the processes more complex so that it is often difficult to separate natural and anthropogenic causes of seagrass loss.

Experience from various parts of northern Australia suggests that episodic losses of hundreds of square kilometres of seagrass are associated with extreme weather events such as some cyclones and floods (Poiner and Peterkin 1996). In the Gulf of Carpentaria in 1985, cyclone Sandy caused the loss of 151 km^2 of seagrass, representing ~20% of the entire Gulf's seagrass area. In 1991–92 several hundred square kilometres of seagrass disappeared from Torres Strait, possibly because of high turbidities resulting from flooding of the Mai River in Papua New Guinea. Furthermore, ~900 km^2 of seagrass was lost in Hervey Bay in 1992–93, possibly because of high turbidities resulting from flooding of the Mary and Burrum Rivers, and run-off turbulence from cyclone Fran three weeks later (Preen and Marsh 1995). Such events can cause extensive damage to seagrass communities through severe wave action, shifting sand, adverse changes in salinity and light reduction (Heinsohn and Spain 1974; Kenyon and Poiner 1987; Preen and Marsh 1995; Preen *et al*. 1995). Recovery and recolonization after large-scale losses of tropical seagrasses may take a decade or more (Poiner and Peterken 1996).

Halophila ovalis, a preferred food species of dugongs, appears to be particularly sensitive to light reduction, with the duration and frequency of light-deprivation events apparently being the primary factors affecting the survival of this seagrass in environments that experience transient light deprivation (Longstaff *et al.* 1999). During light-deprivation experiments the biomass of *H. ovalis* declined rapidly and recovered slowly, with a complete die-off occurring after 30 days of deprivation (Longstaff *et al.* 1999). Members of the genus *Halophila* occur at greater depths than other species of tropical seagrasses and this sensitivity to light reduction is a plausible explanation of the large-scale loss of deep-water seagrasses in Torres Strait (Poiner and Peterkin 1996) and Hervey Bay (Preen *et al*.1995).

To date, the approach to seagrass protection has largely been through marine parks and fishing industry closures to prevent structural damage to seagrass beds through trawling. There have been few attempts to protect seagrass beds from adverse impacts on ecosystem processes associated with land use. Localities that provide shelter and water conditions ideal for seagrasses are often the target for port developments and at the down-stream end of severely affected catchments (Lee Long and Coles 1997). As identified by Lee Long and Coles (1997), research is urgently required to describe the response of seagrasses to natural and human factors and to establish *(1)* acceptable levels of change in response to such factors, and *(2)* the water-quality conditions that lead to these changes.

Incidental catch

Accidental entangling in gill- and mesh-nets set by commercial fishers is considered a major, but largely unquantified, cause of dugong mortality in many countries (Perrin *et al.* 1996). Systematic collation of data on the incidence of dugong by-catch in commercial fisheries has not been attempted by observer programmes. No data are available on the take of dugongs by lost or discarded nets, although drowning in these nets occurs.

The relationship between tides, bottom topography, turbidity and patterns of netting needs investigation. In relatively shallow bays with large tidal fluctuations and high turbidity, seagrass meadows are largely intertidal. In such circumstances, dugongs and netters are all forced to use intertidal areas on the high tide, increasing the chances that dugongs will be caught. This is likely to be the cause of the relatively high frequency of reports of dugongs drowning in nets from areas such as Shoalwater Bay on the Central Queensland coast.

Acoustic alarms (pingers) are proving effective at reducing the mortality of the harbour porpoise, *Phocoena phocoena*, in gill-nets (Trippel *et al*. 1999), and such alarms are increasingly seen as the solution to the problem of marine mammals drowning in nets. The auditory capabilities of the West Indian manatee range from 0.4 to 46 KHz (Gerstein and Gerstein 1999), spanning the range of acoustic alarms (10–12 kHz) (Trippel *et al.* 1999). The effectiveness of the use of acoustic alarms in reducing the mortality of dugongs in nets has not been tested. Given the dugong's specialist habitat requirements, it will also be important to test whether their use reduces the habitat available to dugongs.

Shark nets set for bather protection can be another source of dugong mortality. Between 1962 and 1995, shark nets set on swimming beaches in Queensland netted >800 dugongs (Baden Lane, QDPIFF, personal communication). Most animals caught in shark nets die (Paterson 1990). Twenty-five dugongs drowned in shark nets in Queensland between 1989 and 1993 (Queensland Boating and Fisheries Patrol personal communication), which reflects both the reduction in the dugong population in the area over which the shark nets occur and a reduction in the number of nets set especially in areas with a history of dugong deaths. In most dugong habitats, baited hooks have replaced shark nets, but nets remain at five localities near Cairns and three near Mackay (Anon. 1998; Queensland Department of Primary Industries, personal communication 1999).

Hunting mortality

Dugong hunting is culturally significant to many Aboriginal and Torres Strait Islander communities in northern Australia (Marsh 1996). Australia's indigenous peoples consider dugong hunting to be an important expression of their identity. Dugongs are caught for their meat, and for the oil which is extracted by boiling the parts of the dugong not used for food, such as the head. Dugong oil is used as a panacea for aches, pains and many illnesses. A dugong yields about 35% of its body weight in useable meat and fat (Nietschmann 1984) and on average ~18 L of oil (Smith 1987). The meat of dugongs often ranks highest among traditional foods, and no celebration is considered complete without dugong on the menu. The skilled hunter enjoys considerable prestige in the community (Marsh 1996).

In the Western Islands of Torres Strait the dugong harvest in the 1990s has been estimated as of the order of 1000 per year (Marsh *et al*. 1997). Since the 1960s, Torres Strait Islanders have migrated to mainland Australia in large numbers resulting in nearly as many Islanders living in the coastal cities of Queensland as in Torres Strait (Beckett 1987). This migration has the potential to change the spatial distribution of dugong hunting (Ponte *et al*. 1994) along the northern Australian coast.

There are no contemporary records of levels of directed takes in Australian waters by nationals from Papua New Guinea (legal under the Torres Strait Treaty) and Indonesia (illegal takes). In Torres Strait and parts of the Northern Territory and Western Australia, these takes may be locally significant.

Vessel strikes

Vessel strikes are a major cause of mortality for Florida manatees (Wright *et al.* 1995). The results of Gerstein and Gerstein (1999) suggest that the West Indian manatee possesses a limited low-frequency hearing sensitivity and therefore have difficulty detecting, as well as locating, approaching boats from safe distances. The relevance of these results to dugongs is unknown because the anatomy of the dugong ear differs from that of the manatee (Darlene Ketten, personal communication). Although there are few records of dugong deaths due to vessel strikes in Australian waters, increasing vessel traffic in the dugong's range increases the likelihood of strikes. Areas where there are extensive shallow areas used by regionally important populations of dugongs close to recreational boating facilities are particularly at risk (e.g. Moreton Bay near Brisbane, and Missionary Bay near Cardwell, North Queensland, ~200 km north of Townsville).

Ecotourism

The expansion of ecotourism has resulted in the establishment of tourism operations involving dugong-watching cruises in Shark Bay and on Ningaloo Reef in Western Australian and in Moreton Bay in Queensland. The effect of this activity on the animals is unknown.

Acoustic pollution

There has been no formal attempt to study the effect of acoustic pollution from boat traffic on the dugong. Acoustic pollution could be particularly important in areas with large tidal ranges and little seagrass below the low tide mark. Presumably, high levels of vessel traffic in such areas could prevent dugongs from using available intertidal seagrass meadows.

In Moreton Bay, dugongs seem to avoid shallow areas in the western bay where the level of vessel traffic is high, despite some of these areas being historically important sites for commercial exploitation of dugongs (Preen 1992). Habitat loss is also a plausible explanation for reduced use of this area by dugongs (Abal *et al.* 1998), thus the impact of vessel traffic is unproven. Defence Force exercises are conducted at several localities within the dugong's range in Australia including Shoalwater Bay, the most important dugong habitat in the Great Barrier Reef Region south of Cape York (Marsh in press). The exercises include surface and underwater explosion of bombs, amphibious landings, and firing of shells (Anon. 1997). There have been no reports of dugong mortality as a direct result of these undersea detonations. Such explosions have the potential to cause indirect effects to the dugong such as injury, social disturbance, displacement or habitat damage (Anon. 1997). The risk of adverse effects on dugongs from Defence Force activities must be evaluated in the context of the environmental protection afforded by these activities in comparison with those of other land users along the Queensland coast.

Seismic surveys are an essential component of offshore oil and gas exploration and are used to study rock strata below the sea floor. Marine seismic surveys use high-energy, low-frequency sound produced by arrays of air-guns (Richardson *et al.* 1995) which are designed to project very strong sounds downward through the water. Considerable sound propagates horizontally as well (Richardson and Malme 1993). The sounds produced by air-gun arrays have most of their energy in the frequency range of 10–100 Hz, although some specialized surveys may have energy in the 500 Hz to 2 kHz range (R. D. McCauley personal communication), close to the frequency of sounds made by dugongs (Anderson and Barclay 1995). Effects might include *(1)* interference with the animal's natural acoustic communication signals, *(2)* damage to their hearing systems and *(3)* behavioural changes including disturbance reactions, ranging from brief alterations in behaviour to short- or long-term effects on individuals or populations (Richardson and Malme 1993; McCauley 1994). In Australian waters much of this seismic survey is occurring in the north and north west, particularly on the North West Shelf of Western Australia (McCauley 1994), at least some of which is likely to be important dugong habitat. Low-impact seismic surveys are permitted in all zones within marine protected areas in Western Australia (Preen 1998). Although to date there has been no documented evidence of marine seismic surveys being detrimental to populations of dugongs in Australia, there have been no detailed studies.

Chemical pollutants

Dugongs in northern Australia accumulate high levels of heavy metals with age (Denton *et al*. 1980). There is no evidence to suggest that the accumulation of heavy metals is unnatural or particularly harmful to dugongs, as it appears to be a response to the manner in which seagrasses store these minerals. However, metal levels can be so high that dugong meat may be unsuitable for human consumption. Where ports are established to load metal ores in areas with significant populations of both dugongs and indigenous hunters (e.g. Bing Bong near the mouth of the McArthur River, Northern Territory), this issue requires consideration in the design and operation of storage and loading facilities.

Four dugongs from Townsville and nine dugongs from Mornington Island in the Gulf of Carpentaria were analysed for pesticides in 1978. Lindane was detected in livers of all animals. Heptachlorheploxide was detected in the liver of one animal from Mornington, and dieldrin in two from Townsville and two from Mornington. All levels were very low (Heinsohn and Marsh 1978).

In 1996, fat samples collected from three dugong carcasses washed onto Queensland beaches (Mackay, Bowen ~90 km south of Townsville, and Townsville) were tested for environmental contaminants. Concentrations of polychlorinated dibenzo-p-dioxins and dibenzofurans were high relative to those of most marine mammal samples collected from both the Northern and Southern Hemispheres (Haynes *et al.* 1998). Organochlorine pesticides and polychlorinated biphenyl congeners have been implicated in reproductive and immunological abnormalities observed in marine mammal populations (Kuiken *et al.* 1994; Johnston *et al.* 1996). The significance of their occurrence in dugongs is unknown.

Disease

Dugongs are susceptible to a wide range of diseases, some of them infectious or parasitic. Blair (1981) lists an array of parasitic infestations of Sirenia. Specimens were obtained from 15 dugongs found along the north-eastern coast of Queensland. Six animals were infected by helminths; two by unidentified parasites and the one dugong in captivity showed a severe bacterial infection (Campbell and Ladds 1981). Identifications of disease were not determined conclusively for six animals. A species of *Cryptosporidium*, a small apicomplexan protozoan inhabiting the respiratory and gastrointestinal tracts of a wide range of vertebrates, was found in the small intestine of a dugong from Hervey Bay, Queensland (Hill *et al.* 1997). It is not known whether *Cryptosporidium* can complete its life cycle in the dugong, whether the infection cycles within a herd, or whether the animals can become infected from an external source. Work is in progress to establish the prevalence of *Cryptosporidium* in dugongs (Hill *et al.* 1997).

Conservation strategy

Australian waters

Australia has international obligations for dugong conservation because of several international conventions, including the Torres Strait Treaty, the Biodiversity Convention, the Convention for the Protection of the World's Cultural and Natural Heritage, the Convention on the Conservation of Migratory Species of Wild Animals, and the Convention on International Trade of Endangered Species of Wild Animals. We consider that Australia also has a special responsibility for dugong conservation because it provides one of the last strongholds for dugong populations and the most extensive coastline in the dugong's range where risks from coastal development are low (see Anon. 1996*b*).

Most of the management regimes in place to protect Australia's dugongs are predicated on the assumption that there are, and will continue to be, relatively low levels of anthropogenic impact. This is because dugongs occur mostly in the remote north of Australia. However, in response to the recently documented declines in dugong abundance on the urban coast of Queensland between Dunk Island and the southern boundary of the Great Barrier Reef Marine Park (Marsh *et al*. 1996), the Australian and Queensland governments agreed to several measures including a resolution not to issue permits for traditional hunting south of Cooktown. The most controversial measure was to establish a two-tiered system of Dugong Protection Areas (DPAs) in the Great Barrier Reef region in which gill- and mesh-netting is greatly restricted or banned (seven Zone-A DPAs totalling 2407 km^2)

or subject to lesser modifications designed to reduce the probability of a dugong drowning after entangling in a commercial net (eight Zone-B DPAs totalling 2243 km^2) (Fisheries Regulation No. 11 1997 [Queensland]; Marsh in press). An additional DPA of 1703 km^2 in which gill- and mesh-netting practices have been modified was established in Hervey Bay, immediately south of the region. Thirty-eight non-indigenous commercial fishing licences were cancelled as a result of a voluntary buy-back associated with these initiatives. The resultant controversy has drawn attention to the sustainability of dugong hunting by indigenous peoples in remote communities. Such hunting is mostly unregulated, despite calls from some indigenous leaders for cooperative management.

This decline of the dugong along part of the eastern coast of Queensland suggests that, if Australia is to fulfil its international obligations and special responsibilities for dugong conservation, a more directed management approach is required. The challenge is to develop integrated dugong conservation strategies involving all stakeholders. These strategies must contribute to maintaining dugong populations at present or higher levels and to facilitate the recovery of depleted populations, while providing for the sustainable, traditional use of dugongs by Aborigines and Torres Strait Islanders, which is a Native Title right.

Unless human values change dramatically, we believe that it will be impossible to eliminate anthropogenic impacts on the dugong throughout its vast and remote range. Given the difficulty of identifying stock boundaries and the capacity of dugongs to move across jurisdictional boundaries, it will be important to co-ordinate management initiatives across jurisdictions. This discussion assumes that highest priority will be given to areas for which Australia has international obligations – i.e. Torres Strait, and World Heritage Areas such as Shark Bay and the Great Barrier Reef region.

Given the difficulty in detecting trends in dugong abundance, particularly at low densities (Marsh 1995*b*), the objectives of maintaining dugong numbers at present or higher levels and facilitating the recovery of depleted populations will not be achieved if the only trigger for management intervention in an area is a demonstratively declining population. As pointed out by Wade (1998), it is often potentially easier to detect the circumstances that are likely to lead to a decline in abundance of a marine mammal than it is to detect a decline *per se*. Methods have recently been developed in the USA (Wade 1998) for identifying populations of marine mammals with levels of human-caused mortality that could lead to depletion, taking account of the uncertainty of available information. Unfortunately, this technique cannot yet be used reliably to assess the status of the dugong, because we do not yet have the data required to estimate the necessary parameters. Once these data are available, the technique should have application in remote areas where traditional hunting is the major adverse factor and the dugong harvest can be recorded. In contrast, this approach is likely to have limited application in areas where there are multiple adverse effects on dugongs because of the difficulty of reliably detecting and estimating mortality in such circumstances, especially incidental mortality.

Areas where hunting is the major impact. Research is underway to obtain the information necessary to estimate the parameters to calculate the number of dugongs that can be harvested sustainably from a nominated area using the 'potential biological removal method' (Wade 1998), and the technique should be applicable to dugongs by 2002. This will enable sustainable catch quotas to be calculated for indigenous communities as the basis for negotiating co-operative management arrangements. As such arrangements will require the active participation of the relevant indigenous communities, priority should be given to communities where the traditional owners are keen to participate. Such support is unlikely unless there is a parallel commitment from government to develop a long-term strategy for the training, career structure and resourcing of indigenous community rangers, so that they may participate effectively in dugong management and research programmes. The Turtle and Dugong Hunting Management Plan developed by the Hope Vale Community on Cape York in association with the Great Barrier Reef Marine Park Authority is a useful model for community-based management of dugong hunting.

If the number of dugongs hunted in an area each year is close to or greater than the sustainable harvest, co-operative management will need to address all sources of mortality, as well as the sustainability of indigneous hunting. Other sources of mortality (e.g. from gill- or mesh-netting or from boat strikes) will need to be reduced to as close to zero as possible, preferably through closures in the hunting grounds. Such actions would reflect the spirit of the Australian Law Reform Commission (Anon. 1986), which recommends the following priorities: *(1)* conservation, *(2)* indigenous hunting and *(3)* recreational and commercial hunting and fishing activities.

Areas where there are multiple impacts including incidental mortality. Suppose the coastal waters comprising potential dugong habitat in a region are divided into *n* management zones, with N_i as the estimated dugong population of management zone *i*. Then the number of dugongs (*N)* killed in the whole region each year can be estimated by a simple model:

$$N = \sum_{i=1}^{n} M_i N_i \qquad (1)$$

where M_i is the annual probability of a dugong being killed in zone *i*. This model is applicable even if individual dugongs move between management zones, provided that the relative numbers of dugongs in the various zones remain stable. If the number of dugongs in a zone or the probability of a dugong being killed vary temporally, the model could be further extended to include seasonal or other temporal components.

Choosing zones for closure. The overall effect of reducing M to zero will clearly be greatest in zones in which the probability of an individual dugong being killed is highest and which support the greatest numbers of dugongs throughout the period under consideration. If M is spatially heterogeneous, areas in which it is high are clearly important targets for closure to activities that cause dugong mortality. These are typically areas where the overlap of habitat use by dugongs and the source of mortality are greatest. Causes of high overlap include the physical nature of the site, e.g. narrow movement corridors. These areas of high overlap are probably best identified by means of records of dugong carcasses showing evidence of human-induced mortality.

Priority should be given to feeding areas and breeding areas (if known) that consistently support the largest number of dugongs. If absolute estimates of population size or density are not available, an index of population size or density, such as that obtained from aerial surveys, will be an appropriate surrogate on which to identify such areas. Preen (1998) recommends that factors to be considered in the establishment of dugong sanctuaries include adequate size (to incorporate the home ranges of dugongs), quality of habitat, control of netting, control of mining, local support and appropriate enforcement. Additional factors to be considered include the seasonal movement of dugongs in the higher latitude parts of their range, the need to protect movement corridors and the maximum spacing that will still allow gene flow between sanctuaries (Marsh in press). If several candidate areas can achieve the same conservation benefit, sanctuaries should be selected to minimize the socio-economic effects of closure.

*Choosing when and where to reduce rather than eliminate threats***.** Reducing threats in a zone (e.g. by modifying rather than banning netting, or by introducing speed limits rather than banning boat traffic) is likely to be more politically acceptable, but less effective and harder to enforce than complete closure to these activities. Hence, such actions are most appropriate in zones in which the probability of dugong mortality is low, which support lower numbers of dugongs than areas targeted for closure and where it is practicable to provide effective enforcement. Such zones may also be used as buffer zones around the closed areas, if enforcement is adequate to prevent operators spilling over into the closure areas.

*Comparing the effectiveness of management options***.** Provided the relative sizes of M_i and N_i can be estimated for various zones, Equation 1 enables the potential effectiveness of various packages of management options to be compared. Such comparisons are possible, even if the absolute magnitude of dugong mortality and the absolute size of the dugong population are not known. Such an evaluation assumes that the relative density of dugongs in the various zones does not change as a result of the management measures.

In the long term, the relative density of dugongs should increase in the closed zones relative to the remainder. Thus, habitat protection in closed zones is crucial. Habitat protection in areas where the regulations are modified to reduce mortality is also important, but not as important as for the closed zones.

Implications for dugong conservation outside Australia

A survey by the World Resources Institute rates the risks from coastal development as medium to high for much of the dugong's range outside Australia (Anon. 1996*b*) because of high levels of human population growth and rapid rates of industrialization. The dugong is probably subject to the effects of gill- and mesh-netting throughout most of this range (Perrin *et al.* 1996). In view of these multiple impacts, we consider that the optimum conservation strategy is to identify areas that still support significant numbers of dugongs and to set these areas aside as dugong sanctuaries. All known direct adverse impacts should be minimized in these sanctuaries and the seagrass habitat protected, including protection from the effects of land-based inputs. The establishment of such areas should reduce dugong mortality provided the areas chosen consistently support high numbers of animals. The long-term effectiveness of these areas will depend on whether high-quality dugong habitat can be maintained. This will hinge on the capacity to control land-based inputs. For example, areas where anthropogenic impacts other than fishing are low are more likely to be effective than areas targeted for industrial development.

Candidate sanctuary areas exist in the dugong's range outside Australia. There is no evidence of an overall reduction in the dugong's range (although as discussed above there is evidence of a reduction in its area of occupancy). We consider that it is likely that dugong numbers are higher than previously supposed in many areas. For example, following the death of at least 37 dugongs during the 1983 Nowrez oil spill it was feared that dugongs might have been extirpated from the Arabian Gulf. Aerial surveys in the region established that these fears were unjustified and that the Arabian Gulf population was 7310 ± 1300 (s.e.) dugongs (Preen 1989*a*). Recent fixed-wing aircraft and helicopter surveys have confirmed that dugongs still occur in two areas where they had been presumed to be locally extinct: Ryukyu Islands in south-western Japan (Toshio Kasuya personal communication 1998) and in a marine park in eastern Malaysia (Marsh unpublished 1999).

In most of the developing countries that comprise the dugong's range it will be impractical to use aerial surveys, as has been done in Australia, to identify these significant dugong areas. More economical survey and research techniques, such as interviews, should be used at least initially, as suggested by Marsh and Lefebvre (1994) and detailed in Aragones *et al.* (1998). The risk is that the areas identified will be too far apart to ensure continued gene flow; however, the preliminary genetic data from South-East Asia suggest an encouragingly high level of genetic diversity (Tikel 1998).

An Action Plan for Dugong Conservation in the Philippines was developed at a workshop held in Davao City, Mindanao, in November 1998 with the objective of attaining 'an ecologically viable and stable population of dugongs throughout the Philippines for the benefit of present and future generations'. The Plan identified actions to address the needs of research, protection, law enforcement, monitoring, information, education and communication, sustainable development, training and capacity building, and to obtain sources of funds. High priority was given to the identification and establishment of sanctuary areas, socio-economic impediments to conservation, and community-based management. The concept of a regional dugong workshop for South-East Asia received wide support from international delegates at the meeting. Following adverse publicity resulting from a spate of dugong deaths in the Johore Straits in early 1999, the Malaysian Government made a commitment to using the dugong as an umbrella species for coastal management.

These developments are very encouraging. Nonetheless, the likely difficulty of managing adverse influences on dugongs in highly populated developing countries demonstrates the importance of the remote regions of tropical Australia to dugong conservation; this was emphasized by a recent workshop on the status of marine mammals in South-East Asia (Perrin *et al.* 1996). Thus, it is also important that the agencies responsible for environmental management in the remote tropical regions of Australia outside the Great Barrier Reef region take a more pro-active and comprehensive approach to dugong conservation than they have attempted to date (Preen 1998).

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