Contributed Paper

Rapid Assessment of Risks to a Mobile Marine Mammal in an Ecosystem-Scale Marine Protected Area

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Abstract: *Ecosystem-scale networks of marine protected areas (MPAs) are important conservation tools, but their effectiveness is difficult to quantify in a time frame appropriate to species conservation because of uncertainties in the data available. The dugong (*Dugong dugon*) is a mobile marine species that occurs in shallow inshore waters of an ecosystem-scale network of MPAs (the Great Barrier Reef World Heritage Area [GBRWHA]). We developed a rapid approach to assess risk to dugongs in the region and evaluate options to ameliorate that risk. We used expert opinion and a Delphi technique to identify and rank 5 human factors with the potential to adversely affect dugongs and their sea grass habitats: netting, indigenous hunting, trawling, vessel traffic, and poor-quality terrestrial runoff. We then quantified and compared the distribution of these factors with a spatially explicit model of dugong distribution. We estimated that approximately 96% of habitat of high conservation value for dugongs in the GBRWHA is at low risk from human activities. Using a sensitivity analysis, we found that to decrease risk, commercial netting or indigenous hunting had to be reduced in remote areas and the effects of vessel traffic, terrestrial runoff, and commercial netting had to be reduced in urban areas. This approach enabled us to compare and rank risks so as to identify the most severe risks and locate specific sites that require further management attention.*

Keywords: *Dugong dugon*, Delphi technique, fishing effects, Great Barrier Reef World Heritage Area, habitat conservation value, marine protected area, rapid risk assessment, spatial risk assessment

Evaluación Rápida de Riesgos para un Mamífero Marino Móvil en una Área Marina Protegida a Escala de Ecosistema

Resumen: *Las redes de áreas marinas protegidas (AMPs) a escala de ecosistema son herramientas importantes para la conservación, pero es difícil cuantificar su efectividad en un marco temporal apropiado para la conservación de especies por las incertidumbres en los datos disponible. El dugongo (*Dugong dugon*) es una especie marina móvil que ocurre en aguas costeras someras en una red de AMPs a escala de ecosistema (el área de Patrimonio Mundial Gran Barrera Arrecifal [APMGBA]). Desarrollamos un método rápido para evaluar el riesgo para los dugongos en la región y evaluar las opciones para aminorar ese riesgo. Utilizamos la opinión de expertos y una técnica Delphi para identificar y clasificar 5 factores humanos con el potencial de afectar adversamente a los dugongos y sus hábitats de pastos marinos: uso de redes, cacería por nativos, pesca con redes de arrastre, tráfico de navíos y escorrentías terrestres de baja calidad. Posteriormente cuantificamos y comparamos la distribución de estos factores con un modelo espacialmente explícito de la distribución de dugongos. Estimamos que aproximadamente 96% del hábitat con alto valor de conservación para los dugongos en APMGBA tiene un bajo riesgo por actividades humanas. Mediante un análisis de sensibilidad, encontramos que para reducir el riesgo, se tendría que disminuir el uso de redes comerciales y la cacería por nativos en áreas remotas y que los efectos del tráfico de navíos las escorrentías terrestres y el uso de redes comerciales tendrían que reducirse en las áreas urbanas. Este método nos permitió comparar y*

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clasificar riesgos para identificar los riesgos más severos y localizar los sitios específicos que requieren mayor atención.

Palabras Clave: APMGBA, área marina protegida, *Dugong dugon*, efectos de la pesca, evaluación de riesgos espacial, evaluación rápida de riesgos, sitio de Patrimonio Mundial Gran Barrera Arrecifal, técnica Delphi, valor de conservación de hábitat

Introduction

Marine protected areas (MPAs) are intended to manage or protect defined areas of sea through legislative arrangements and management infrastructure (Kelleher & Kenchington 1992). They are typically established to increase the likelihood that fisheries will be sustainable, biodiversity and species will be conserved, cultural values will be preserved, or some combination of these goals (Kelleher et al. 1995). Ecosystem-scale networks of MPAs are increasingly favored over small, isolated ones, as demonstrated by the recently declared Northwestern Hawaiian Island Marine National Monument and the proposed global network of high-seas marine reserves (Roberts et al. 2006). Such initiatives are potentially effective tools for conserving marine mammals (Hoyt 2005), but the capacity of a specific MPA network to protect marine mammals is difficult to quantify in a time frame appropriate to species conservation.

The uncertainties associated with evaluating the effectiveness of single-species management approaches are generally high. It is impossible to detect even large changes in most populations of marine mammals with current levels of investment in surveys, survey technology, and survey design (Taylor et al. 2007). Evaluating the effectiveness of ecosystem approaches such as networks of MPAs is made even more difficult because data are generally lacking and the way in which different components of the ecosystem are linked is poorly understood. At the broad spatial scales of networks of MPAs, information is inevitably scarce as a result of multiple factors, including time, expertise, and cost constraints (Galloway et al. 2002).

Marine mammals are threatened by various human factors, and regulatory decisions to manage such activities are typically made with incomplete scientific information. However, a good management decision should not require large numbers of precise estimates to trigger warranted management actions (Taylor et al. 2007). Decision-support tools, such as spatial risk assessments in geographical information systems (GIS), can assist in the rapid assessment of risks to marine mammals by incorporating spatially explicit models of species distribution with qualitative and quantitative information on the distribution of the anthropogenic impacts (Pull & Dunning 1995). Thus, a spatial risk-assessment approach potentially provides managers with maximum return for minimal investment in data collection by identifying areas where management intervention should provide the greatest positive result for the resources of concern (Theobald 2003).

The Great Barrier Reef World Heritage Area (GBRWHA) of Queensland, Australia, is the world's largest World Heritage site (approximately 348,000 km^2) and second-largest MPA (Fig. 1). Globally significant populations of the dugong (*Dugong dugon*) or sea cow inhabit the shallow inshore waters of the GBRWHA and are one of several explicit reasons for the region's World Heritage listing (GBRMPA 1981). Dugongs are listed globally as vulnerable by the World Conservation Union (IUCN 2006) and under schedule 3 of the Queensland Nature Conservation (Wildlife) Regulation of 1994. They have high biodiversity value as the only herbivorous mammal that is strictly marine and the only extant member of the family Dugongidae, very high cultural and nutritional value to indigenous Australians, and are regarded as a flagship species by nonindigenous Australians. All these factors make dugong management a high priority for managers of the GBRWHA.

The management challenges in the remote region of the GBRWHA off Cape York Peninsula are different from the challenges along the urban coast, where dugong numbers are seriously depleted (Fig. 1; Marsh et al. 2005). Off Cape York, mean dugong density are 7 times higher than along the urban coast (0.145 compared with 0.020 dugongs/km^2; Grech & Marsh 2007). Nonetheless, population-viability-analysis (PVA) modeling suggests that the current level of indigenous harvest is unsustainable (Heinsohn et al. 2004). These regional differences are reflected in the management arrangements. For example, the network of dedicated Dugong Protection Areas (DPAs) is restricted to the urban coast and was implemented in 1997 under fisheries legislation to protect dugongs from bycatch in the commercial fisheries (Marsh 2000). Nonetheless, individual dugongs can move hundreds of kilometers in a few days (Sheppard et al. 2007), and all dugongs in the GBRWHA are considered part of a single stock (McDonald 2006). Therefore, management activities need to be conducted and evaluated at the scale of the entire GBRWHA (>300,000 km^2).

The GBRWHA was rezoned recently to maximize the protection of marine biodiversity through a comprehensive and representative multiple-use regime (Fernandes et al. 2005). The rezoning established an

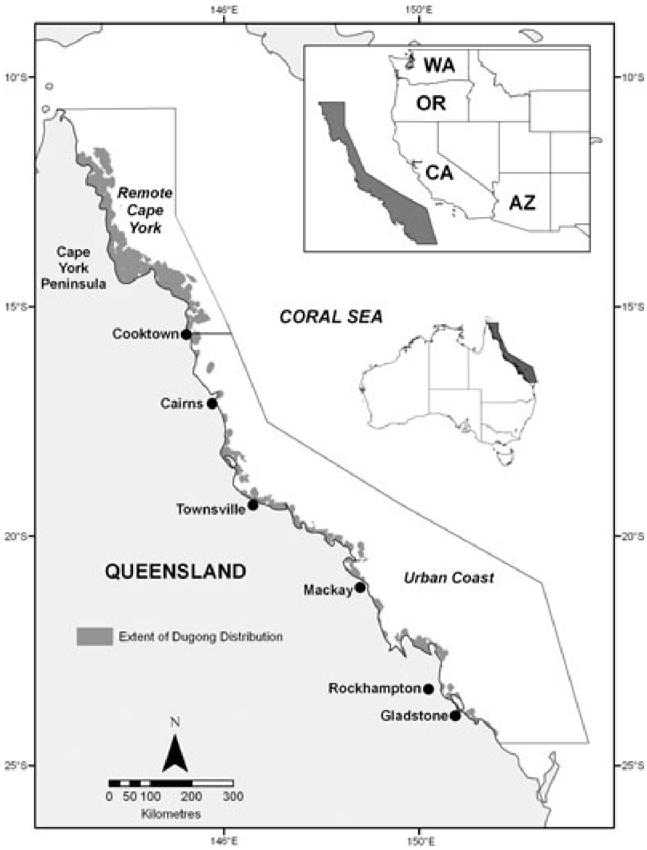

Figure 1. Extent of the Great Barrier Reef World Heritage Area (GBRWHA) off the coast of Queensland, Australia. Major regional cities are shown. The GBRWHA is divided into the remote Cape York and urban coast subregions as illustrated. The region shaded in grey is the extent of dugong distribution modeled by Grech and Marsh (2007). Inset is the extent of the GBRWHA relative to the west coast of the United States.

ecosystem-scale network of no-take areas covering approximately 33% of the Great Barrier Reef Marine Park and the contiguous Great Barrier Reef Coast Marine Park. The 2004 changes to the zoning arrangements upgraded dugong protection in accordance with the program's biophysical operating principles (Fernandes et al. 2005) by increasing no-take areas closed to commercial netting and trawling. The rationale behind this approach for conserving mobile species such as dugongs is that area closures restrict the areas that can be fished and typically eliminate fishing from areas that consistently support high densities of the bycatch species. Area closures are not designed to eliminate the likelihood of individuals of mobile species being caught as bycatch; rather, they reduce the risk to the bycatch population by eliminating the likelihood of bycatch to that proportion of the population that uses the closed area, either temporarily or permanently. When designed appropriately, closures can be very effective in reducing the bycatch of marine mammals (Murray et al. 2000). Nevertheless, the rezoning of the GBRWHA does not control the other factors that have negative effects on dugongs or their sea grass habitats, including indigenous hunting, vessel traffic, and poor water quality resulting from terrestrial runoff (McKenzie et al. 2000; Marsh et al. 2002; Heinsohn et al. 2004).

Several state and federal government agencies manage the various human activities that affect dugongs in the GBRWHA across jurisdictions, which makes it a challenge to quantify the extent to which the species is actually protected. Although the GBRWHA is one of the world's most well-studied and managed marine ecosystems, knowledge of the distribution and relative effect of the various human activities is inadequate. For example, the current level of dugong mortality caused by any one of the major causes of human-induced mortality is unknown (Marsh et al. 2002). This makes it difficult to quantify the impacts of the hazards to the GBRWHA dugong population. In the face of this uncertainty, we developed a spatial risk-assessment approach to allow rapid assessment of the level of risk to dugongs from human factors under the current zoning and management arrangements in the GBRWHA and to evaluate options to ameliorate that risk. Our approach can be generalized to situations in which ecosystem-scale MPA networks are used to protect mobile marine mammals.

Methods

Prioritizing Dugong Conservation

Grech and Marsh (2007) used spatial information from a time series of dedicated aerial surveys conducted at spatial scales of about 30,000 km^2 approximately every 5 years (between 1986 and 2005) to develop a spatially explicit dugong population model. This model mapped the relative density of dugongs across the GBRWHA at the scale of dugong management units (cells) of 4 km^2, which is the spatial scale recommended for managers under criterion B of the World Conservation Union (IUCN) Red List (IUCN 2001).

Grech and Marsh (2007) classified each dugong management unit as of low, medium, or high conservation value on the basis of the relative density of dugongs estimated from the model and a frequency analyses. This approach assumes that dugong density is a robust index of a region's conservation value for dugongs. This assumption is justified because density estimates are regarded as suitable surrogate measurements of habitat use (Hooker & Gerber 2004) and no critical habitats for dugongs have been identified other than the sea grass meadows, where they spend most of their time. By using the time series of data collected over 19 years, the model accounts for temporal changes in the use of various regions by dugongs,

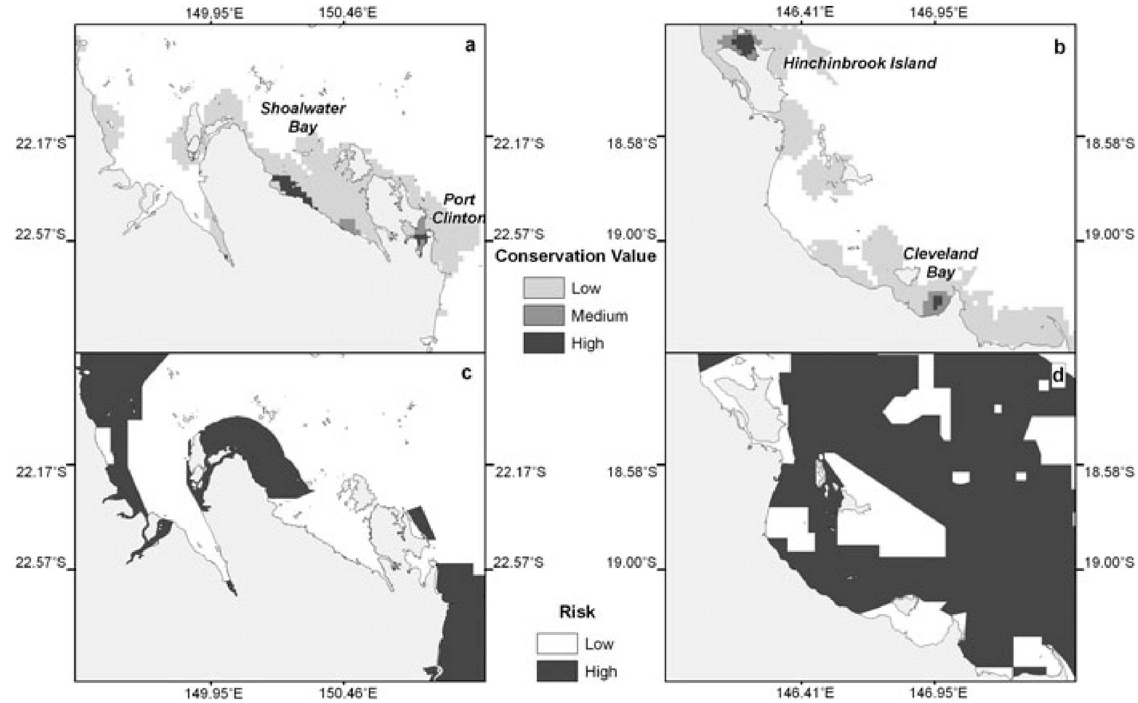

Figure 2. Models of dugong management units with high, medium, and low dugong conservation value (Grech & Marsh 2007) in (a) Shoalwater Bay region and (b) the region between Cleveland Bay and Hinchinbrook Island and (c, d) models of regions of high and low risk from all anthropogenic activities along the urban coast of the Great Barrier Reef World Heritage area. Dugongs are not limited to the regions shown in (a) and (b); they also occur at low densities along the protected inshore coast of the GBRWHA (Fig. 1), defined by Grech and Marsh (2007) as areas of low conservation value.

including movements resulting from events such as sea grass dieback.

The areas of highest relative density along the urban coast are in the Shoalwater Bay region, including Port Clinton (Fig. 2a), north of Hinchinbrook Island (Fig. 2b), and Cleveland Bay (Fig. 2b). In the remote north the areas of high dugong conservation value are near Friendly Point and Port Stewart and between Lookout Point and Princess Charlotte Bay (Fig. 3a). Dugongs are not limited to the regions shown in Figs. 2 and 3; they also occur at low densities along the entire protected inshore coast of the GBRWHA (Fig. 1). Most of this region is classified by Grech and Marsh (2007) as of low conservation value to dugongs. We used Grech and Marsh's (2007) model of dugong distribution as the basis for quantifying the protection afforded to dugongs by the current zoning and management regimes in the GBRWHA.

Rapid Assessment of Risk to Dugongs from Anthropogenic Activities

In our spatial risk assessment, we followed Sutur (1993) and estimated the risk to dugongs from various anthropogenic factors in the GBRWHA by identifying the hazards; quantifying the exposure of dugongs to these hazards; and estimating the risk to dugongs from the hazards.

HAZARD IDENTIFICATION

We identified from the literature, especially Marsh et al. (2002), the anthropogenic factors that represent hazards to the dugong population in the GBRWHA as (1) incidental mortality in gill and mesh nets (Marsh 2000) and in prawn (shrimp) trawlers (R. Coles, personal communication), (2) sea grass habitat loss associated with agricultural runoff, industrial runoff, oil spills, harbor dredging, or a combination of these activities (McKenzie et al. 2000), (3) prawn trawling, which can damage bottom habitats (Marsh et al. 2002), (4) vessel strikes (Hodgson 2004; Greenland & Limpus 2006), (5) displacement of dugongs from key habitats as a result of vessel traffic (Hodgson & Marsh 2007), and (6) poaching and legal indigenous hunting (Heinsohn et al. 2004).

EXPOSURE QUANTIFICATION

We quantified the spatial distribution of the 5 factors that contribute to those hazards: commercial gill and mesh netting, trawling, indigenous hunting, vessel traffic, and risk of poor-quality terrestrial runoff from adjacent catchments as outlined later. The marine political boundaries that delineate netting are the dugong protection areas (Fisheries Act of 1994; Queensland Department of Primary Industries and Fisheries [QDPI&F]), the Great

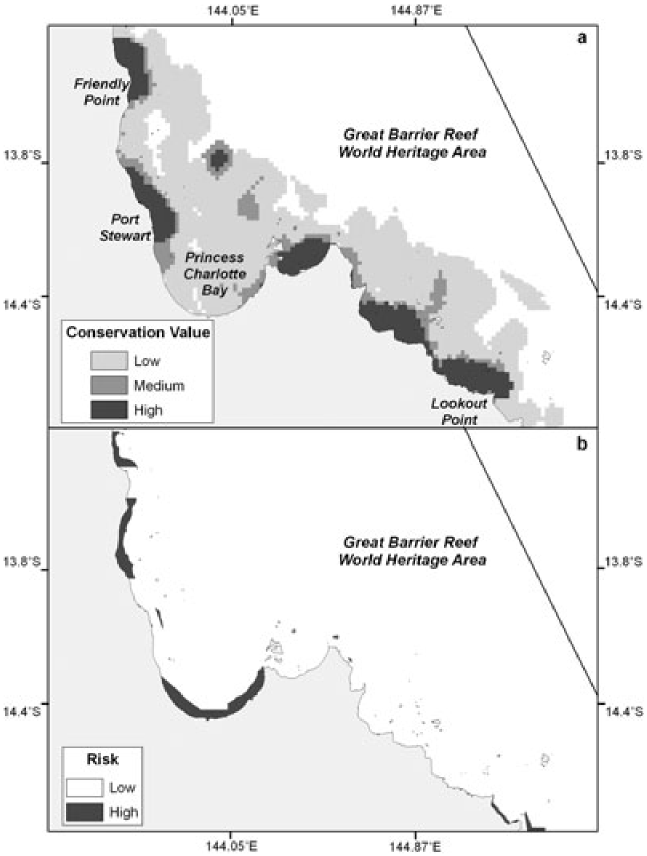

Figure 3. Model of dugong management units with (a) high, medium, and low dugong conservation value (Grech & Marsh 2007) and (b) regions of high and low risk from all anthropogenic activities in the remote Cape York region of the Great Barrier Reef World Heritage Area (GBRWHA). Dugongs are not limited to the regions shown in (a); they also occur at low densities along the protected inshore coast of the GBRWHA (Fig 1), defined by Grech and Marsh (2007) as areas of low conservation value.

Barrier Reef Marine Park Zoning Plan of 2003 (GBRMPA), the Great Barrier Reef Coast Marine Park Zoning Plan of 2004 (Queensland Environmental Protection Agency [Qld EPA]), and the boundaries of ports as designated by the relevant port authorities. Five levels of regulated netting restrictions, ranging from no netting permitted to gear restrictions, are relevant to dugongs in the GBRWHA (Table 1). Trawling is delineated by the same marine political boundaries as netting, with the East Coast Trawl Management Plan 2000 (QDPI&F) providing additional spatial and temporal restrictions. Trawling is either prohibited or allowed within zones of the Great Barrier Reef Marine Park. Because we conducted a risk assessment and did not attempt to quantify potential dugong mortality, we assumed that the spatial extent of commercial netting and trawling was limited only by these regulations (i.e., we did not consider the socioeconomic reasons for fishers not to operate in an area).

We derived a model of relative inshore (<4 m long) and reef (>4 m) recreational-vessel traffic from the number of recreational boats registered within regional centers bordering the GBRWHA (Queensland Department of Transport 2004). The Queensland Department of Transport tracks the number and geographic location of registered vessels by the postcode of its owner's residence. Seventy-five percent of registered vessels were inshore boats that are unlikely to operate offshore (>15 km from the coast) (S. Sutton, personal communication). The remaining 25% were recreational reef vessels that can operate in all waters of the GBRWHA. Using information on the geographic location of the zip code of its owner's residence, we assigned registered vessels along the GBRWHA coast to their closest port or marina. We assumed that a vessel was used only in the region it was registered, all vessels (reef and inshore) operated within 15 km from the coast (not including islands), and 25% of registered vessels also operated in waters outside that region. Each dugong management unit was assigned the number of registered vessels of its closest regional center (of 19 available, mean Euclidean distance between centers = 90 km). Using the knowledge of experts in the region's recreational and commercial fleet, vessel traffic per dugong management unit was rated as follows: low, number of registered vessels <300; medium, 300–1000; medium high, 1000–3000; high, >3000. Commercial vessels are generally larger than recreational vessels; function for transport, fishing, or tourism; and operate within designated shipping lanes or areas open to commercial fishing or tourism. Strikes by commercial vessels occasionally cause dugong mortality in the GBRWHA, but we could not model commercial-vessel traffic because many vessels do not operate in the waters surrounding their port of registration. In our model, commercial transit lanes and ports where commercial vessels dock were classified as high risk to dugongs, so this omission should not affect our assessment.

The Great Barrier Reef Water Quality and Action Plan of 2001 (GBRMPA) was devised with information on land clearing, cultivation, and the quality of water discharged from rivers entering the GBRWHA to model the risk of poor-quality terrestrial runoff entering inshore areas from catchments (high, medium-high, medium, and low risk). Flood plumes (carrying terrestrial runoff of poor water quality) extend to a maximum of 20 km from the coastline of the GBRWHA (GBRMPA 2001). To derive a layer of risk from terrestrial runoff, we assigned the level of risk of the closest catchment (of 35 available, mean distance between catchments = 133 km) to each dugong management unit that was within 20 km from the coastline. Dugong management units beyond 20 km of the coastline were considered at low risk of terrestrial runoff. This model assumed that any given area within the GBRWHA

Table 1. Individual and composite ratings of the relative risk of anthropogenic activities to dugongs and their habitats developed by experts through a Delphi technique.

Activity	*Composite rating of activity relative to other impacts*[a]	*Impact level within risk factor*	*Rating of impact level within risk factor*[b]	*Composite rating of impact level*[c]
Indigenous hunting	40	not present	0	0
		present	100	40
Netting	32	NP/HR[d]	0	0
		level-1 restrictions	20	6.4
		level-2 restrictions	50	16
		level-3 restrictions	80	25.6
		limited restrictions	100	32
Trawling	5	prohibited	0	0
		not prohibited	100	5
Vessel traffic	11.5	low risk	0	0
		medium risk	40	4.6
		medium-high risk	70	8.1
		high risk	100	11.5
Terrestrial runoff	11.5	low risk	0	0
		medium risk	40	4.6
		medium-high risk	70	8.1
		high risk	100	11.5

[a]*Derived by ranking the relative importance of the effects of anthropogenic activities out of 100.*
[b]*Derived by ranking the relative importance of the individual impact levels of anthropogenic activities out of 100.*
[c]*Derived by calculating the relative importance of impact levels of anthropogenic activities on the basis of the composite rating of activities relative to other impacts.*
[d]*Not permitted or highly restricted.*

was influenced by only one catchment and that the influence of catchments extended only to within 20 km of the coast.

We obtained spatial information on the distribution of indigenous hunting of dugongs from the GBRMPA, which collected information on dugong hunting in 2004 through interviews conducted by marine parks staff (T. Stokes, personal communication). This information provided a qualitative (presence–absence) assessment of the spatial extent of indigenous hunting in various regions. On advice from the GBRMPA, we assumed indigenous hunting was not present over approximately 5.4 km from the coast or in waters >5 m deep (C. Turner & T. Stokes, personal communication).

We intersected digital GIS layers of the spatial risk from netting, trawling, vessel traffic, poor-quality terrestrial runoff, and indigenous hunting to form a composite coverage.

RISK ESTIMATION

Information on dugong mortality, trauma, or stress from the 5 human factors identified across various areas of the GBRWHA was only available from the Queensland Marine Wildlife Stranding and Mortality Database (Greenland & Limpus 2006). This database grossly underestimates dugong mortality especially in remote areas because an unknown percentage of carcasses are not recovered or made available for necropsy, and indigenous catches are not reported. In light of this uncertainty and other data limitations, we used expert knowledge to rank risks to dugongs. Expert knowledge is used widely to resolve uncertainty and compensate for incomplete information in conservation planning (Bojórquez-Tapia et al. 2003), and it was essential to the rezoning of the GBRWHA (Fernandes et al. 2005). We used a Delphi technique (Veal 1992) at a meeting of experts in the region's commercial fisheries, indigenous issues, species conservation, and dugong ecology and management. The experts weighted the relative risk to dugongs and their habitats from each of the 5 human factors and then weighted the relative importance of the components of each factor (Table 1). The experts agreed that indigenous hunting had the greatest relative effect on the GBRWHA dugong population, followed in decreasing order of effect by commercial netting, vessel traffic, terrestrial runoff, and commercial trawling. The experts also agreed that where one of the factors was not present, or posed only a low risk to dugongs, a rating of zero was appropriate.

The ratings for each factor were imported to the composite coverage of hazards generated above and overlayed with the spatial model of dugong conservation value to provide an overall matrix of dugong protection. We conducted a sensitivity analysis of the different levels of our composite coverage of impacts to define a cutoff score at which the combined influence of the 5 hazards could be considered to be of low risk to dugongs (Store & Kangas 2001). We found that the use of scores ≤40 made a trivial difference to the overall results, and scores >40 were swamped by the presence of indigenous

Table 2. Area (km^2) and percentage of dugong management units with high, medium, and low conservation value in the entire Great Barrier Reef World Heritage Area (GBRWHA) and the urban coast and remote Cape York subregions of the GBRWHA, where the risk of all anthropogenic activities[a] is low under the current zoning and management arrangements.

Conservation value[b]	GBRWHA area (%)	Urban coast area (%)	Remote Cape York area (%)
High	2303 (96)	173 (100)	2137 (96)
Medium	2088 (93)	246 (95)	1782 (93)
Low	19793 (72)	4944 (42)	14776 (94)

[a]*Defined as weighted composite impact index ≤ 40.*
[b]*As defined by Grech and Marsh (2007).*

hunting. We assumed that dugong management units have a high risk from anthropogenic activities when 2 or more hazards are present and a low risk when 1 or no activity is present. Hazards were weighted on their relative impact on dugongs, and indigenous hunting received the greatest relative impact with a score of 40; thus, we used an overall impact index of ≤40 to represent a low level of risk to dugongs and an index of >40 to represent a high level of risk (Figs. 2c,d, & 3b). Dugongs inhabit the shallow, inshore protected regions of the GBRWHA; therefore, Figs. 2c, d, and 3b overestimate the actual protection afforded to the species because we modeled the composite impact index over the extent of the entire GBRWHA. Finally, by sequentially removing human factors from the matrix of dugong protection, we assessed the sensitivity of the model to changes in their presence and distribution.

Results

Under the current GBRWHA zoning and management arrangements, 96% of dugong management units of high conservation value are at low risk from anthropogenic activities (100% on the urban coast and 96% in the Cape York region) (Table 2). Ninety-three percent of units with medium conservation value are at low risk (95% along the urban coast and 93% in the Cape York region), as are 72% of units with low conservation value (42% along the urban coast and 94% in the Cape York region).

By sequentially removing human factors from our matrix of dugong protection, we assessed the sensitivity of our model to changes in their presence and distribution (Table 3). All units with a high conservation value to dugongs on the urban coast were at low risk from anthropogenic impacts, so removing additional hazards had no effect on those units. Removing the risk of terrestrial runoff and vessel strike or commercial netting produced a low risk from anthropogenic activities for approximately all dugong management units of medium conservation value and for nearly all units of low conservation value. Removing indigenous hunting and trawling provided a negligible increase in the proportion of units of medium and low conservation value designated as low risk.

When commercial netting was removed in dugong management units of high conservation value along the remote coastal waters of Cape York, approximately 100% of the area was at low risk from the combined impact of anthropogenic factors. When indigenous hunting was removed in units of high conservation value, all of these management units were classified as at low risk. Removing terrestrial runoff, vessel traffic, and commercial trawling from the matrix in Cape York region provided no increase in the proportion of units of high conservation value designated as low risk. Dugong management units with medium conservation value exhibited a similar pattern. Removing commercial netting and indigenous hunting provided the greatest increase in the proportion of medium-value conservation units with low-risk designations (almost 100% and 99%, respectively); eliminating terrestrial runoff, vessel traffic, and trawling made comparatively less difference.

Table 3. Percentage of dugong management units (sensu Grech & Marsh 2007) of high, medium, and low conservation value in the entire Great Barrier Reef World Heritage Area and the urban coast and remote Cape York subregions with a low risk from anthropogenic activities under various hypothetical scenarios.

	Entire GBRWHA			Urban coast			Cape York		
Activities	high	med	low	high	med	low	high	med	low
Current zoning and management arrangements	96	93	72	100	95	42	96	93	94
No netting	100	100	99	100	100	97	100	100	100
No trawling	96	93	75	100	95	45	96	93	97
No netting and trawling	100	100	99	100	100	97	100	100	100
No risk from terrestrial runoff	96	93	79	100	97	54	96	93	97
No vessel traffic	96	93	77	100	96	53	96	93	94
No risk from terrestrial runoff and vessel traffic	96	93.	98	100	100	98	96	93	97
No indigenous hunting	100	99	74	100	95	44	100	100	97

Our spatial risk-assessment approach identified areas of high and medium conservation value that would benefit from additional management intervention because the current level of risk to dugongs is high. These areas included the coastal waters between Port Stewart and Friendly Point in the remote Cape York region (Fig. 2).

Discussion

In our model the present ecosystem-scale network of MPAs and associated management arrangements resulted in dugongs being categorized as at low risk from human impacts for approximately 96% of management units with high conservation value and 93% with medium conservation value in the 348,000-km^2 GBRWHA. By testing the sensitivity of the matrix of dugong protection, we identified those effects that, if removed, would provide the greatest additional benefit to dugong conservation in the region, assuming the present patterns of use by people and dugongs (Table 3). In remote Cape York we found that removing commercial netting or indigenous hunting would result in virtually all dugong management units of high and medium conservation value being designated low risk (Table 3). Along the urban coast removing the risk of terrestrial runoff and vessel strike or commercial netting would result in all dugong management units of medium conservation value and nearly all units of low conservation value being categorized as low risk.

Accuracy of Estimates

Uncertainty in information that contributes to management decisions can result in poor management actions (Carey et al. 2005). We attempted to minimize the uncertainty in our analysis of the relative risk to dugongs and their habitats from each of 5 human factors by basing our assumptions on quantitative and qualitative information made available through the literature and expert opinion. Nevertheless, owing to the current lack of information on the characteristics and spatial distribution of factors that affect dugongs in the GBRHWA, our models still contain uncertainties that are difficult to quantify. As new information becomes available, our assessment can easily be improved by reevaluating our assumptions, updating the geographic layers, and adjusting the expert weightings of hazards.

Removal of commercial netting or indigenous hunting in the Cape York region (Fig. 1) produced a low risk from anthropogenic activities for almost all dugong management units of high and medium conservation value. Nevertheless, the PVA modeling of Heinsohn et al. (2004) suggests that indigenous hunting is not sustainable off the coast of Cape York. If this is correct we have overestimated the area in which dugongs have a low level of risk from anthropogenic activities by not including areas in which indigenous hunting is the only human impact. Fortunately, the GBRMPA and the Queensland EPA are currently working with traditional-owner groups to inform and manage hunting by indigenous peoples in the GBRWHA (Havemann et al. 2005), so we believe our analysis is robust to this uncertainty.

Our assessment of the sensitivity of the matrix of dugong protection to removal of various factors (Table 3) does not mean that the consequential reduction in anthropogenic mortality would be the same for removal of each factor. Our estimates of relative risk on the basis of expert opinion are tentative. More robust comparisons will require (1) accurate data on the actual levels of anthropogenic mortality from impacts in various areas of the GBRWHA, (2) additional information on the genetic structuring of the dugong stock, and (3) information on the risks to dugongs moving between areas of occupancy in the GBRWHA. This information will take many years to obtain.

Dugongs undertake macroscale (>100 km) movements between bays and mesoscale (15–100 km) movements within bays between sites of significant sea grass habitat (Gales et al. 2004; Marsh et al. 2004, 2005; Sheppard et al. 2007). These movements are generally restricted to within 20 km off the coast, but no discrete movement corridors have been identified (Sheppard et al. 2007). If defined corridors exist, Grech and Marsh's (2007) spatial model of dugong conservation value will have to be revised because it classifies potential movement corridors as having low conservation value relative to other sites within the dugong's range in the GBRWHA on the basis of their low dugong density. There is currently limited protection for dugongs moving between sites of significant habitat along the urban coast (Fig. 2).

Lessons Learned

Along the urban coast, removing commercial netting or simultaneously removing the hazards of poor-quality terrestrial runoff and vessel traffic would provide the greatest improvement in protection for dugong management units of medium and low conservation value. Removing trawling or indigenous hunting would have a minimal impact on protection, largely because of the voluntary moratorium on hunting currently implemented by most local indigenous groups. To maximize the likelihood of dugong populations recovering on the urban coast, management should aim for an anthropogenic mortality target of zero as advocated by Marsh et al. (2005) on the basis of potential biological-removal modeling (Wade 1998). This management approach necessitates (1) asking indigenous groups to continue their moratorium on hunting, (2) banning commercial gill netting along the urban coast of the GBRWHA, and (3) addressing the hazards of vessel strike and poor-quality terrestrial runoff.

The protection afforded by the ecosystem-scale network of MPAs in the GBRWHA is limited by the inability of MPAs to mitigate all the factors that threaten the marine environment, including activities in the adjacent coastal catchments. Hoyt (2005) and Jameson et al. (2002) describe a basic principle that should be observed when designing MPAs: appreciate the links between marine, coastal, and terrestrial ecosystems. Thus, potential anthropogenic effects from contaminated terrestrial runoff, vessel traffic, indigenous hunting, climate change, and pollution should also be recognized and managed when designing MPAs. As for most large-scale MPAs, effective management of all anthropogenic activities in the GBRWHA will require increased cross-jurisdictional collaboration.

Spatial Risk Assessments as a Tool for Rapidly Assessing Ecosystem-Scale MPA Networks

By using a spatial risk-assessment approach, we were able to compare and rank risks to identify the most severe risks first and to locate specific sites that require further management attention. Dugong management units of high and medium conservation value in the coastal waters between Port Stewart and Friendly Point (Fig. 3) in the Cape York region are at comparatively high risk from anthropogenic activities, largely because of the limited restrictions on commercial netting. For MPAs to be effective in species conservation over large geographic regions, it is essential to manage effectively those areas where the species are most vulnerable (Roberts et al. 2001). It may be unreasonable to protect a species by restricting anthropogenic factors that pose a hazard to the species for an entire region's coastline, but management plans can be successful by protecting sites where species are abundant. Furthermore, targeting management initiatives to ensure these areas are resilient to anthropogenic impacts will further enhance species conservation goals.

Ecosystem-scale networks of MPAs are implemented over broad spatial scales and quantitative information on the distribution of species, such as mobile marine mammals, and the effects of anthropogenic factors on them is inevitably scarce. Uncertainty and incomplete information can be a major constraint to the decision-making process (Bacic et al. 2006); however, spatial risk assessments can rapidly evaluate the risk to mobile marine mammals from a variety of activities that adversely affect them in an uncertain environment.

We believe that rapid spatial risk assessments are potentially valuable for managing species that range over large areas that are managed across jurisdictions, such as World Heritage sites and other large-scale marine-planning initiatives. For example, a spatial risk assessment could be used to asses the status of risk for New Zealand's endangered Hector's dolphin (*Cephalorhynchus hectori*), an inshore species threatened by multiple factors, including incidental mortality in gill nets (Slooten et al. 2000). This management tool could also be used to assess existing MPAs, including the Galapagos Marine Reserve (>133,000 km^2). The Galapagos Marine Reserve, which is also a World Heritage site, supports other species of mobile marine wildlife and is threatened by commercial fishing activities and tourism.

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