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# *A spatial assessment of the risk to a mobile marine mammal from bycatch*

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ABSTRACT

1. Several species of marine mammals are at risk of extinction from being captured as bycatch in commercial fisheries. Various approaches have been developed and implemented to address this bycatch problem, including devices and gear changes, time and area closures and fisheries moratoria. Most of these solutions are difficult to implement effectively, especially for artisanal fisheries in developing countries and remote regions.
2. Re-zoning of the Great Barrier Reef World Heritage Area (GBRWHA) in 2004 closed 33% of the region to extractive activities, including commercial fishing. However, the impact of re-zoning and the associated industry restructuring on a threatened marine mammal, the dugong (*Dugong dugon*), is difficult to quantify. Accurate information on dugong bycatch in commercial nets is unavailable because of the large geographic extent of the GBRWHA, the remoteness of the region adjacent to the Cape York Peninsula where most dugongs occur and the artisanal nature of the fishery.
3. In the face of this uncertainty, a spatial risk-assessment approach was used to evaluate the re-zoning and associated industry restructuring for their ability to reduce the risk of dugong bycatch from commercial fisheries netting.
4. The new zoning arrangements appreciably reduced the risk of dugong bycatch by reducing the total area where commercial netting is permitted. Netting is currently not permitted in 67% of dugong habitats of high conservation value, a 56% improvement over the former arrangements. Re-zoning and industry restructuring also contributed to a 22% decline in the spatial extent of conducted netting.
5. Spatial risk assessment approaches that evaluate the risk of mobile marine mammals from bycatch are applicable to other situations where there is limited information on the location and intensity of bycatch, including remote regions and developing countries where resources are limited.


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KEY WORDS: bycatch; netting; spatial risk assessment; marine mammals; dugong; *dugong dugon*; GBRWHA

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## INTRODUCTION

The single greatest threat to many stocks of marine mammals is incidental entanglement and mortality in fishing gear (bycatch) (Read and Rosenberg, 2002). Many species of marine mega-fauna are at risk of extinction from fisheries bycatch (Lewison *et al*., 2004). This threat has increased in frequency and intensity over time as a result of human population growth and the industrialization of fisheries, and is expected to continue and rise (Read *et al*., 2006).

Several countries have developed comprehensive scientific and management programmes to evaluate interactions between marine mammals and fisheries (Read and Wade, 2000). This approach is generally beyond the means of developing nations and is difficult to implement in small-scale fisheries and in remote areas (Marsh *et al*., 2003). For example, the Potential Biological Removal technique (PBR), the approach required by the *US Marine Mammal Protection Act*, requires estimates of the absolute abundance and life history parameters of a marine mammal stock and the bycatch of the fishery. Estimates of bycatch are usually collected through an observer programme (Wade, 1998), which can be impractical to implement in an artisanal fishery (Lewison *et al*., 2004). In addition, the PBR approach does not incorporate threats to marine mammal stocks other than anthropogenic-induced mortality. Such threats include habitat degradation, ecosystem changes, depletion of the prey base, predation or disease (Taylor *et al*., 2007). Even the uncertainty analysis approach advocated by Lewison *et al*. (2004) may require more information than is available to inform effective solutions to the bycatch problem.

Several techniques have been developed and implemented to reduce the risk of fisheries bycatch to marine mammals including: (1) devices and gear changes that mitigate bycatch; and (2) fisheries management policies such as time and area closures and fisheries moratoria (Lewison *et al*., 2004). The concept of risk has two elements: (1) the likelihood of something happening; and the (2) consequences if it happens (Norton *et al*., 1996). Technological solutions can be very effective at reducing either or both these elements of risk. For example, bycatch reduction devices (Hall *et al*., 2000) reduce the consequence of bycatch by allowing an animal that has been caught in fishing gear to escape. However, such solutions are generally difficult to implement effectively for artisanal fisheries in developing countries and remote areas, largely because of cost (Marsh *et al*., 2003). Temporal closures restrict fishing for particular species for a period of time or season and are typically designed to reduce the consequences of bycatch when they are particularly serious; e.g. when the bycatch species is breeding. Spatial (area) closures restrict the areas that can be fished and typically eliminate fishing from areas which 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).

Area closures have been used since the early 1980s in association with other fisheries management policies to reduce the risk of commercial netting to a threatened marine mammal, the dugong (*Dugong dugon*) in the 348 000 km$^2$ Great Barrier Reef World Heritage Area (GBRWHA) and adjacent Hervey Bay. In 1998, management policies including 16 Dugong Protection Areas (DPAs) (Marsh, 2000), were also introduced under fisheries legislation to further reduce incidental dugong mortality in commercial nets. Foreshore and offshore set or drift nets were prohibited in seven Zone A DPAs of total area 2407 km$^2$. Less-restrictive modifications were introduced in eight Zone B DPAs of total area 2243 km$^2$ (Marsh, 2000).

The GBRWHA was re-zoned in 2004 to maximize the protection of marine biodiversity through a comprehensive and representative multiple-use regime (Fernandes *et al*., 2005). The re-zoning established an ecosystem-scale network of marine protected areas (MPAs) covering approximately 33% of the Great Barrier Reef Marine Park and the contiguous Great Barrier Reef Coast Marine Park, resulting in a network of area closures about the size of England. The 2004 changes to the zoning arrangements upgraded dugong protection in accordance with the programme's biophysical operating principles (Fernandes *et al*., 2005), by increasing area closures on commercial netting and trawling. Although biodiversity protection was the primary reason for this re-zoning, the Biophysical Operational Principles developed to guide the management agency in developing the network of no-take areas included a commitment to ensure that about 50% of high priority dugong habitats were closed to commercial fishing activities, including gill and mesh nets used in the Queensland East Coast Inshore Fin Fish Fishery (Fernandes *et al*., 2005).

The Australian government provided a structural adjustment package to assist fishers adversely affected by the 2004 re-zoning. The package was also intended to: (1) prevent displacement in fishing effort to other fishing grounds that would result in unsustainable ecological or economic impacts; and (2) to reduce overall effort in concordance with area closures (Marine Protected Area News, 2006). The Queensland Department of Primary Industry and Fisheries (QDPI&F) also implemented a policy to control latent effort (allocated effort that is not currently deployed) in fisheries under their control including the Queensland East Coast Inshore Fin Fish Fishery



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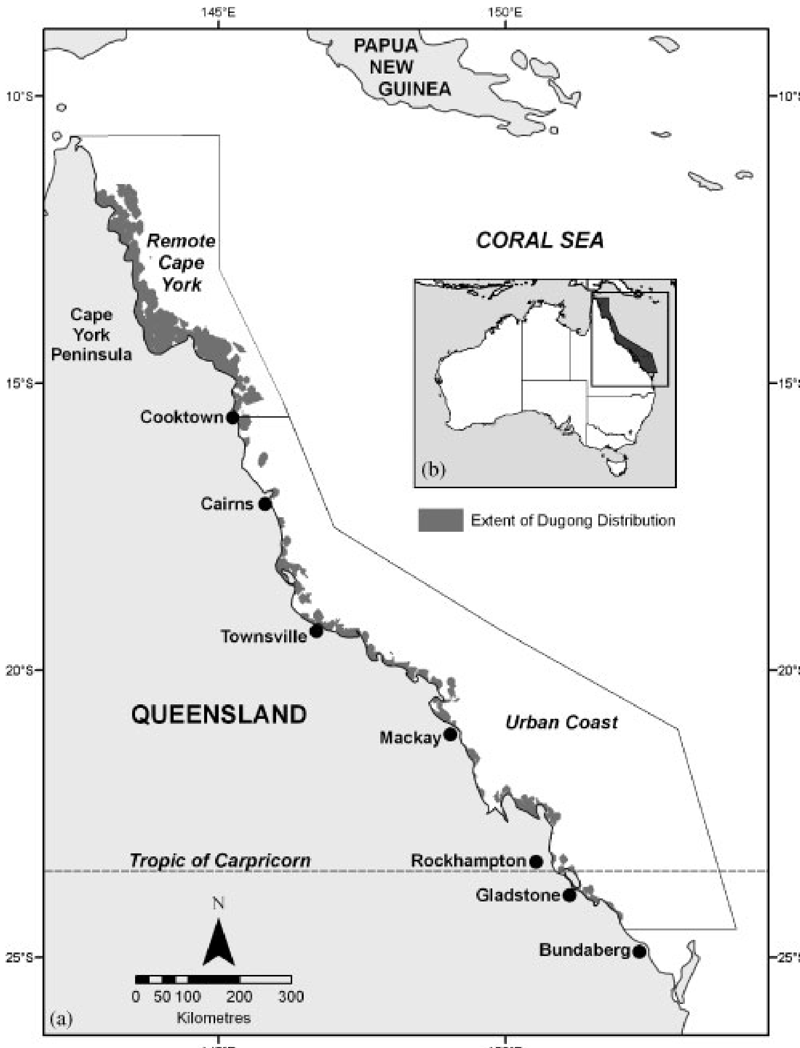


Figure 1. (a) Extent of the Great Barrier Reef World Heritage Area off the coast of Queensland, Australia showing the major regional cities. The GBRWHA is divided into the remote Cape York region and urban coast as illustrated. The region shaded in grey is the extent of dugong distribution modelled by Grech and Marsh (2007). (b) Extent of the GBRWHA relative to Australia.

to ensure their economic sustainability, resulting in a 40% reduction in the number of inshore net licences in 2004 and 2005.

The impact of re-zoning and industry restructuring on the dugong population is difficult to quantify. Although the GBRWHA has won international recognition as one of the world's most advanced networks of MPAs, accurate information on dugong bycatch in commercial nets is unavailable for several reasons: (1) the large geographic extent of the GBRWHA; (2) the remoteness of the region adjacent to the Cape York Peninsula where most dugongs occur (Figure 1); (3) the nature of the fishery, which makes boat-based observer (surveillance) programmes logistically difficult and expensive, largely because of the small size of the fishing vessels; and (4) the lack of observers who are independent of the fishing industry and appropriately trained (Lewison *et al*., 2004).

Uncertainty and incomplete information can be a major constraint to the decision-making process (Bacic *et al*., 2006). Decision-support tools, such as spatial risk assessments in a geographical information system (GIS), can assist in evaluating the risk to marine mega-fauna from bycatch in an uncertain environment. This approach combines spatial data



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on the distribution of a species and anthropogenic impacts (Dunning *et al*., 1995) to identify areas where management intervention is likely to be most effective (Theobald, 2003; Andersen *et al*., 2004). GIS-based spatial risk assessments are particularly valuable in large geographic regions where information is limited as they can incorporate different kinds of quantitative and qualitative spatial data to support the estimation, evaluation and comparison of alternative management interventions.

In this study, a spatial risk assessment approach was used to: (1) provide a rapid evaluation of the capacity of the new management arrangements in the GBRWHA to minimize the risk of dugong bycatch in commercial netting operations based on available data; and (2) inform the 2007 revision of the Queensland East Coast Inshore Fin Fish Fishery management arrangements. The applicability of this approach to other situations where there are uncertainties about the magnitude of the bycatch of marine mega-fauna, including remote regions and developing countries where resources are limited is also assessed.

# METHODS

## Study region

The GBRWHA stretches from 24.5°S to 10.7°S (2300 km) along Australia's north-eastern seaboard (Figure 1). It is the world's largest World Heritage Area and second largest Marine Protected Area (MPA). The GBRWHA is functionally divisible into two distinct management regions based upon remoteness; the developed urban coast and the remote Cape York region (Figure 1). Large regional centres including the cities of Cairns, Townsville and Gladstone, are situated along the urban coast of the GBRWHA, which supports a total population of >800 000 people. In remote Cape York, the population is much smaller (<7000 people) and scattered among small communities separated by large expanses with very little infrastructure.

## Rapid assessment of risk for dugongs from human activities in the GBRWHA

The usual consequence of a dugong being caught in a net is that it drowns (Marsh *et al*., 2005). Dugongs of all sizes, ages and both sexes are caught (Marsh, 1980), suggesting that the likelihood of a dugong drowning in a net is independent of the animal's reproductive value. Thus the likelihood of a dugong being caught in a net should be a robust surrogate of the risk of dugong bycatch. Given that there is no evidence of bycatch selectivity, the probability of a dugong being caught in a net should be a function of dugong density and fishing effort (Marsh, 2000). If fishing effort is banned from an area and that ban is enforced, then the likelihood of dugong bycatch in that area should be reduced to zero, irrespective of whether individual animals use the area permanently or temporarily.

This study followed Suter (1993) and estimated the risk to dugongs in the GBRWHA by: (1) identifying the hazard; (2) quantifying the exposure of dugongs to the hazard; and (3) estimating the risk to dugongs from the hazard.

### *Hazard identification*

Records of bycatch in shark nets set for bather protection (Marsh *et al*., 2005) suggest that dugong numbers declined significantly along the urban coast of the GBRWHA between the early 1960s and 1999. The reasons for this decline are complex and include: (1) accidental mortality in: (a) gill and mesh nets of the Queensland East Coast Inshore Fin Fish Fishery, (b) illegal netting, and (c) nets used in the Queensland shark control programme; (2) seagrass habitat loss associated with agricultural runoff, industrial runoff, oil spills, harbour dredging and/or a combination of these activities (McKenzie *et al*., 2000); (3) prawn (shrimp) trawling; (4) vessel strike (Hodgson, 2004; Greenland and Limpus, 2006); (5) the potential displacement of dugongs from key habitats as a result of vessel activity (Hodgson and Marsh, 2007); (6) poaching; and (7) legal indigenous hunting. Comparable records are not available from the remote north where the major effects are from legal indigenous hunting (Heinsohn *et al*., 2004) and bycatch in commercial gill nets.

### *Exposure quantification*

Marsh's group undertook systematic aerial surveys of the GBRWHA approximately every five years between 1986 and 2005, by flying transects across the depth gradient (Marsh and Saalfeld, 1989, 1990; Marsh *et al*., 1993, 1996; Marsh and Lawler, 2001, 2002). Grech and Marsh (2007) use the composite, spatial information on dugong distribution and relative abundance from these surveys to develop a spatially explicit dugong population model. 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 including movements resulting from events such as seagrass dieback (Marsh and Kwan, in press) (Table 1). Grech and Marsh's (2007) model maps the relative density of dugongs across the GBRWHA at the scale of 4 $km^2$ dugong management units (cells), the spatial scale recommended for managers under Criterion B of the *International Union for Conservation of Nature and Natural Resources Red List* (IUCN, 2001).

Grech and Marsh (2007) classified each dugong managment 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. The resultant map of dugong conservation value was used in this study as the spatial



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Table 1. Evaluation of the assumptions underpinning the analyses

| Assumption | Justification | Risk of false assumption |
|---|---|---|
| Grech and Marsh's (2007) spatially explicit dugong population model accounts for temporal changes in dugong habitat use since 1985. | By using a time series of data collected over 19 years, Grech and Marsh's (2007) model accounts for temporal changes in the use of various regions by dugongs including movements resulting from events such as seagrass dieback (Marsh and Kwan, in press). | Low |
| Since 1985, there has been no decline in the extent of dugong occurrence, although there may be decline in area of occupancy. | There is no evidence that the anthropogenic activities that have caused dugong decline have removed populations at the spatial scale of the management arrangements. This assumption should not increase the uncertainty in the risk assessment for two reasons: (1) the present rather than the past risk of dugong bycatch is assessed; and (2) the spatial scale of dugong management in the GBRWHA is far broader than any reduction in the area used by dugongs within their range in the GBRWHA. | Low |
| The risk to dugongs is nil in zones where: (1) all netting is prohibited or bait netting only permitted; (2) offshore set, foreshore set and drift nets are prohibited; and (3) river set nets are allowed with modification. | The listed restrictions remove netting practices that cause dugong entanglement in gill and mesh nets and are effectively enforced. | Low |
| Netting was not conducted in sections of the 30 nm grids of the January–June 2005 period that did not overlap with commercial netting activities conducted in the 6 nm fisheries grids of the January–June 2004 period. | New area closures and industry restructuring decreased the extent of permitted commercial netting activities, total catch, and effort. | Low |
| The only influences on the distribution of catch between January and June 2004 and January and June 2005 are the area closures associated with re-zoning and industry restructuring. No external factor including environmental conditions affected the catch available to fishers. Anthropogenic factors, including the cost of fuel and the condition of vessels did not influence the distribution of commercial catch and effort. | There is little documented evidence that the catch available to fishers was affected by external factors during January–June 2004 and 2005. Information that is available cannot be quantified spatially across the entire GBRWHA. | Medium |
| No illegal netting occurred | Information on the distribution of illegal net fisheries is unavailable at the scale of this analysis. | Medium |

parameter to determine the protection afforded by the current zoning and management regimes in the GBRWHA.

This approach makes the assumption that the model of dugong density developed from the time series of aerial surveys is a robust index of a region's conservation value for dugongs. This assumption is justified because: (1) specialized areas of high conservation value such as calving or mating areas and migratory corridors have not been identified; and (2) density estimates are regarded as robust surrogates of habitat utilization (Hooker and Gerber, 2004). Nonetheless, Grech and Marsh's (2007) classification scheme may underestimate the past conservation value of some areas along the urban coast by using information collected on dugong distribution and abundance, only since 1985. In this study, it is assumed that there has been no overall decline in the extent of dugong occurrence in the GBRWHA since 1985 (Table 1), a conclusion supported by the aerial survey results.

The areas of highest relative density (high and medium conservation value) along the urban coast are in the Shoalwater Bay region including Port Clinton, north of Hinchinbrook Island, and Cleveland Bay (Figure 2). In remote Cape York, the areas of high dugong conservation value are off Friendly Point and Port Stewart, and between Lookout Point and Princess Charlotte Bay (Figure 3). Dugongs are not limited to the regions shown in Figures 2 and 3, but are also distributed at low density along virtually the entire protected inshore coast of the GBRWHA (Figure 1). Most of this region is classified by Grech and Marsh (2007) as of low conservation value to dugongs.

There are multiple marine legislative boundaries that currently control the distribution of commercial netting in the GBRWHA, as described in Table 2. Together, these arrangements regulate five levels of netting restrictions that are relevant to dugongs in the GBRWHA. Levels 1 and 2 provide dugongs with an assumed nil risk of bycatch from netting activities as no netting is permitted or the permitted netting practices prevent dugong entanglement.

## *Risk estimation*

To derive a single coverage of the *current* spatial extent of bycatch risk, the intersect tool of GIS program ArcGIS® 9.1



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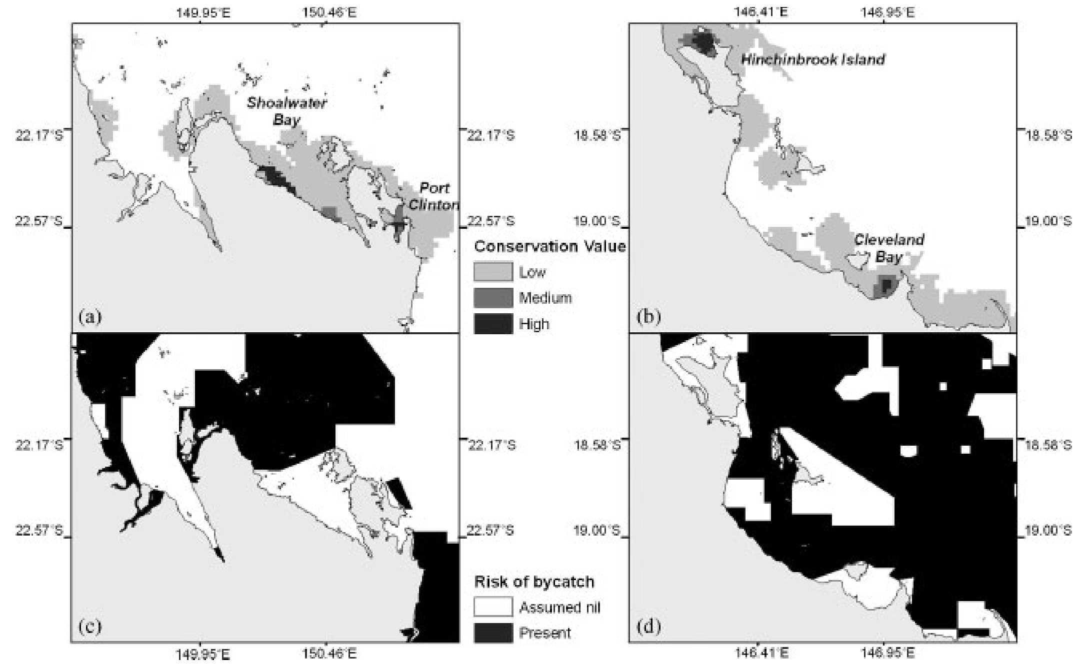


Figure 2. Models of dugong management units with high, medium and low dugong conservation value (a, b) (Grech and Marsh, 2007) plus the current risk of bycatch from commercial netting derived from the five levels of netting restrictions relevant to dugongs (c, d) along the urban coast of the Great Barrier Reef World Heritage Area. a and c represent the Shoalwater Bay region, and b and d the region between Cleveland Bay and Hinchinbrook Island. Dugongs are not limited to the regions shown in a and b, but are also distributed at low density along the protected inshore coast of the GBRWHA (Figure 1), defined by Grech and Marsh (2007) as low conservation value areas.

(Environmental Systems Research Institute, 2004) was used to combine digital layers of multiple marine legislative boundaries that currently control the distribution of commercial netting in the GBRWHA (Table 2; Figures 2 and 3). The resultant coverage was overlayed with the spatial model of dugong conservation value (Grech and Marsh, 2007) to provide an overall spatial matrix of the current likelihood of dugong bycatch.

The corresponding likelihood of dugong bycatch under the former zoning regime was derived by combining the multiple marine legislative boundaries controlling the distribution of commercial netting in the GBRWHA prior to re-zoning with the spatial model of dugong conservation value.

The two matrices of the likelihood of dugong bycatch were used to estimate the proportion of high, medium and low conservation value dugong management units where: (1) netting is currently permitted; and (2) netting was permitted prior to re-zoning.

Commercial catch information was integrated into the risk assessment to provide an empirically derived limit on the spatial extent of commercial netting in the GBRWHA. The QDPI&F monitor catch of the netting industry through compulsory daily logbooks completed by fishers. The information collected in these logbooks includes: (1) the day's catch (weight and species); (2) locations fished; and (3) time spent fishing. This information is then aggregated by QDPI&F into grids of resolution 6 nm.

Information extracted to 6 nm grids was used for the time periods January–June 2004 (pre re-zoning) and January–June 2005 (post re-zoning) to quantify the change in risk to dugongs from bycatch as a result of netting area closures. These time periods were chosen because: (1) temporal closures occur based on the life history of the target fish species making it important to compare similar times of year; and (2) industry restructuring by QDPI&F did not affect the fishery until after January 2004.

For three sites in the January–June 2005 period, catch information was aggregated by QDPI&F to a 30 nm scale because of misreporting of catch and effort information by fishers. Thus, results possibly overestimate the spatial extent of netting in this period as an artefact of the large spatial extent of these grids. To eliminate this false positive, sections of the 30 nm grids of the January–June 2005 period that did not overlap with the 6 nm fisheries grids in the January–June 2004 period where fishing was conducted were removed. The associated error is low as new area closures and industry



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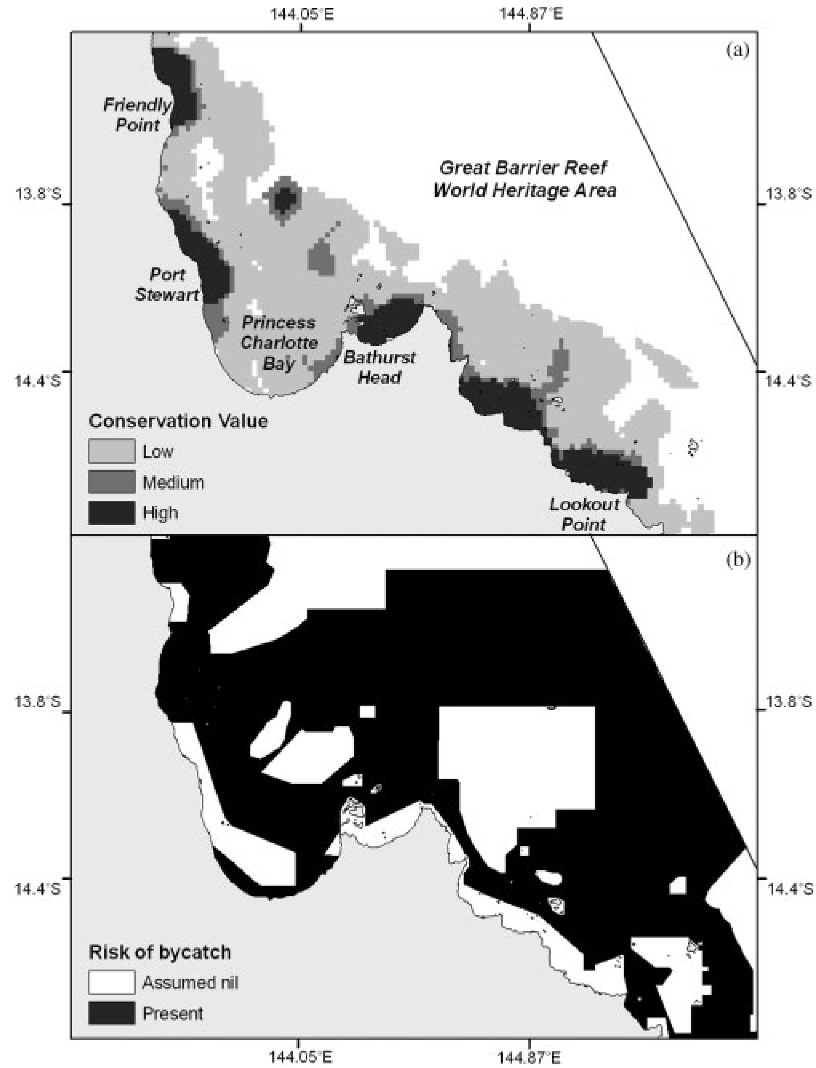


Figure 3. Model of dugong management units with high, medium and low dugong conservation value (a) (Grech and Marsh, 2007) plus the current risk of bycatch from commercial netting derived from the five levels of netting restrictions relevant to dugongs (b) in the remote Cape York region of the Great Barrier Reef World Heritage Area. Dugongs are not limited to the regions shown in a, but are also distributed at low density along the protected inshore coast of the GBRWHA (Figure 1), defined by Grech and Marsh (2007) as low conservation value areas.

restructuring reduced the spatial extent of commercial netting, total catch and effort across all other grids between 2004 and 2005 (Table 1).

Because of the relatively large spatial scale of 6 nm fisheries catch grids, portions of some grids extend into areas where netting is not permitted. These portions were removed by erasing sections of grids that fell outside the region where netting is permitted before and after the 2004 re-zoning. The relative effort for each grid under the current and former zoning regime was calculated as the ratio of the number days spent fishing in a grid/area of that grid where netting was permitted. The output coverages were used to estimate the proportion of areas of dugong management units that netting was conducted: (1) under the current zoning (January–June 2005) and industry arrangements; and (2) under former zoning and before industry restructuring (January–June 2004). Table 1 summarizes and evaluates the assumptions of the analyses.

To quantify change in effort between the two periods, the final coverages of relative effort were converted to a raster grid of cell size 4 $km^2$ (the same scale as the dugong management

Table 2. The five levels of restrictions on commercial netting relevant to dugongs in the GBRWHA.[a] The risk of bycatch of dugongs is low under Level 1 and 2 restrictions

| Level 1 restrictions | Level 2 restrictions | Level 3 restrictions | Level 4 restrictions | Level 5 restrictions |
|---|---|---|---|---|
| All netting prohibited or bait netting only permitted | Offshore set, foreshore set and drift nets prohibited. River set nets allowed with modification[b] | Offshore set nets, nets that are not fixed or hauled prohibited. Restrictions on set mesh nets on the foreshore | Restrictions on mesh netting | Netting permitted under regulations of the Queensland *Fisheries Act* 1994 and *Fisheries Regulations* 1995 |

[a]The marine legislative boundaries that currently control the distribution of commercial netting include: Dugong Protection Areas (DPAs) (*Queensland Fisheries Regulation* 1995; QDPI&F); *Great Barrier Reef Marine Park Zoning Plan* 2003 (GBRMPA); *Great Barrier Reef Coast Marine Park Zoning Plan* 2004 (Qld EPA); Princess Charlotte Bay Special Management Area (GBRMPA); and the boundaries of ports as designated by the relevant port authorities. Prior to the 2004 re-zoning, netting was controlled by: DPAs; the former *Great Barrier Reef Marine Park Zoning Plan*; pre-2004 relevant State Marine Parks (Qld EPA); developmental areas; and port authorities.
[b]Prohibited in Hinchinbrook and Shoalwater Bay along the urban coast.

Table 3. Percentage of dugong management units of high, medium and low conservation value in: (1) the entire Great Barrier Reef World Heritage Area; (2) urban coast; and (3) remote Cape York regions where: (1) the risk of dugong bycatch was assumed to be nil; and (2) no gill-netting actually occurred during: (a) January–June 2005 (after re-zoning and industry restructuring) and (b) January–June 2004 (before re-zoning and industry restructuring). The total area considered here is the known area used by dugongs in the GBRWHA as modelled by Grech and Marsh (2007)

| | Dugong conservation value | Total area ($km^2$) | GBRWHA | | Total area ($km^2$) | Urban coast | | Total area ($km^2$) | Remote Cape York | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Jan–Jun 2004 | Jan–Jun 2005 | | Jan–Jun 2004 | Jan–Jun 2005 | | Jan–Jun 2004 | Jan–Jun 2005 |
| Assumed nil risk of bycatch[a] | High | 2399 | 43 | 67 | 173 | 100 | 100 | 2226 | 38 | 64 |
| | Medium | 2175 | 38 | 50 | 259 | 85 | 95 | 1916 | 30 | 44 |
| | Low | 27 490 | 23 | 34 | 11 771 | 22 | 38 | 15 719 | 25 | 31 |
| No risk of bycatch[b] | High | 2399 | 79 | 96 | 173 | 100 | 100 | 2226 | 78 | 96 |
| | Medium | 2175 | 86 | 91 | 259 | 96 | 95 | 1916 | 85 | 91 |
| | Low | 27 490 | 72 | 80 | 11 771 | 47 | 62 | 15 719 | 89 | 93 |

[a]Risk of bycatch is assumed nil as no netting is permitted or permitted netting practices do not cause dugong entanglement in gill and mesh nets.
[b]There is no risk of dugong bycatch as netting was not conducted.

units). Minor spatial errors were introduced by changing the scale of fisheries grids; but as almost exactly 24 cells of 4 $km^2$ fall inside one 6 nm grid and the output layer was not used for spatial analyses, this minor error will not affect the final result. Each dugong management unit (cell) of the spatial model of dugong conservation value was then assigned the value of the fishing effort that it overlayed for: (1) January–June 2004; and (2) January–June 2005. This information was exported to the statistical program GenStat 8th Edition (Lawes Agricultural Trust, 2005). Frequency distributions of dugong conservation value and effort data did not approxmate a Gaussian distribution and as a result, assumptions of parametric statistical tests were not met; the information instead was analysed with paired Mann–Whitney U tests with $\alpha = 0.05$.

## RESULTS

Under the zoning and management arrangements in operation since January 2005, it is estimated that the risk of dugong bycatch should be nil in approximately 67% (801 $km^2$) of the dugong management units of high conservation value identified by Grech and Marsh (2007), a relative improvement of 56% (573 $km^2$) from the previous arrangements (Table 3). Currently, there is 'nil' risk of bycatch for all high conservation value management units along the urban coast and in 36% (801 $km^2$) of the corresponding units in the remote Cape York (a relative increase of 0% and 68%, respectively). A 'nil' risk of bycatch is present in half (1089 $km^2$) of the management units of medium conservation value (% on the urban coast and 49% off remote Cape York region), a 20% (311 $km^2$) relative increase from the previous zoning and management arrangements.

DPAs now play a relatively minor role in the overall protection of dugongs in the GBRWHA despite their iconic status. Only about 7% (172 $km^2$) of the high conservation value and 11% (232 $km^2$) of the medium conservation value dugong management units where the risk of bycatch should be nil are within the designated DPAs Zone A (foreshore and offshore set or drift nets are prohibited). This is because most of the units of high conservation value to dugongs are in the remote Cape York region and all the designated DPAs are



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along the urban coast. Nonetheless, along the urban coast, all the dugong management units of high conservation value and 90% of the units of medium conservation value where current zoning provides a low risk of bycatch to dugongs are within DPAs Zone A. If the netting restrictions for DPA Zone B were upgraded to the same level as Zone A, the increase in dugong protection would be minimal.

When the spatial effort data are considered, the reduction in bycatch risk to dugongs from the post-2004 management arrangements is even more significant than suggested by the area closures alone. Between January and June 2005, commercial netting did not occur in approximately 96% (2303 $km^2$) of the dugong management units of high conservation value (Table 3), a relative increase of 22% (408 $km^2$) from January–June 2004. Along the urban coast, no units of high conservation value were commercially netted between January and June 2005; the corresponding value in the remote waters off Cape York was 96% (2136 $km^2$). Between January and June 2005, netting was not conducted in 91% (1979 $km^2$) of the units of medium conservation value (95% on the urban coast, and 91% in the remote Cape York region), a 6% (109 $km^2$) relative decrease from the corresponding period in 2004. The mean reduction in netting effort per dugong management unit was statistically significant for the following areas: (1) the entire GBRWHA; (2) the urban coast; and (3) the remote waters off Cape York for dugong management units of high, medium and low conservation value (Table 4).

Four anomalous locations were identified where commercial netting is still permitted in dugong management units of high or medium conservation value and where netting was conducted between January and June 2005. They include the regions surrounding: (1) Bathurst Head; (2) Friendly Point; and (3) Lookout Point off remote Cape York; and (4) the region adjacent to Port Clinton on the urban coast (Figures 2 and 3).

Table 4. Results of the paired Mann–Whitney U tests comparing commercial netting effort for each dugong management unit in the January–June periods of 2004 and 2005 within dugong management units of high, medium and low conservation value in the entire Great Barrier Reef World Heritage Area, urban coast and remote Cape York regions

| | | Dugong conservation value | | |
|---|---|---|---|---|
| | | High | Medium | Low |
| GBRWHA | $n^a$ | 100 | 68 | 1975 |
| | $P^b$ | $<0.001^c$ | $0.001^c$ | $<0.001^c$ |
| Urban coast | $n^a$ | — | 3 | 1531 |
| | $P^b$ | — | — | $<0.001^c$ |
| Remote Cape | $n^a$ | 100 | 65 | 444 |
| York | $P^b$ | $<0.001^c$ | $0.001^c$ | $<0.001^c$ |

[a] Number of dugong management units for each test.
[b] Significance level observed from a paired Mann–Whitney U test.
[c] Highest rank score observed in the January–June 2004 period.

## DISCUSSION

The re-zoning of the GBRWHA in 2004 was designed to maximize biodiversity protection through a comprehensive, adequate and representative multiple-use zoning regime (Day *et al*., 2000). This study found that the resultant area closures significantly reduced the risk of dugong mortality in commercial gill and mesh nets by reducing the area in which commercial netting activities are permitted in dugong habitats of high, medium and low conservation value. The restructuring of the fishing industry further reduced the spatial distribution of netting and overall fishing effort.

### Accuracy of estimates

Catch information from commercial fisheries in Queensland is aggregated to 30 nm and 6 nm grids, and the paths of individual boats are not recorded. Thus the analyses overestimate the distribution of netting activities. Consequently, the proportion of dugong habitats where netting is conducted underestimates the protection afforded to dugongs in the GBRWHA. Finer scale information on the distribution of netting activities would reduce this error.

It is unreasonable to protect a species by restricting activities for the coastline of an entire region such as the GBRWHA. However, Roberts *et al*. (2001) stress the need to effectively manage those areas where the species are most vulnerable. This study assumed that these are the sites of high dugong density, typically seagrass meadows, e.g. Shoalwater Bay, Cleveland Bay and Hinchinbrook Island (Figure 2). Dugongs undertake macro-scale ( > 100 km) and meso-scale (15–100 km) movements between such meadows (Gales *et al*., 2004; Marsh *et al*., 2004, 2005; Sheppard *et al*., 2006). Timed depth recorders show that dugongs track the bottom when undertaking macro-scale movements between meadows leaving them vulnerable to bottom set gill nets. Data from some 70 satellite-tracked dugongs suggest that their movements are individualistic and not restricted to defined movement corridors (Sheppard *et al*., 2006). Nonetheless, if movement corridors occur in areas where commercial netting is permitted and conducted, the results of this study overestimate the protection afforded to dugongs by area closures and industry restructuring by classifying potential movement corridors as low conservation value to dugongs. One way managers could address this problem without more data would be to increase attendance-at-net rules to reduce the consequence of dugong entanglement in a net by increasing the likelihood that it would be released alive.



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The results of this research assume that no illegal netting was conducted within the GBRWHA. Gribble and Robertson (1998) observed vessels of the Queensland east coast prawn trawl fleet consistently trawling in areas where it was not permitted in the remote waters off Cape York. Such lack of compliance most likely results from the limited surveillance and enforcement activities in the remote areas of the GBRWHA. Illegal fishing is less likely to occur in populated inshore areas of the urban coast (Davis *et al*., 2004; Williamson *et al*., 2004), and is becoming less of an issue with the introduction in recent years of vessel monitoring systems. The inability to quantify illegal netting means that the protection afforded to dugongs by area closures in the GBRWHA is probably overestimated by an unknown amount, especially in the remote Cape York region where dugongs are most abundant.

The overall effect of these sources of inaccuracy in this study's analysis is unknown.

## Implications for dugongs in the GBRWHA

Although this analysis indicates that area closures and industry restructuring have reduced the proportion of the dugong's range at risk from bycatch via netting activities, further evaluation of the likely effectiveness of these management interventions will require accurate data on the actual levels of incidental mortality from commercial netting in various areas of the GBRWHA. On the basis of PBR modelling (Wade, 1998), Marsh *et al*. (2005) estimated that management should aim for an anthropogenic mortality target of zero to maximize the likelihood of dugong populations recovering on the urban coast of the GBRWHA. Future dugong management strategies in the GBRWHA should also consider the potential effects of continued commercial netting along the urban coast, especially in the region adjacent to Port Clinton (Figure 2) where netting activities are conducted in a potential dugong corridor between the high conservation value dugong areas of Port Clinton and Shoalwater Bay (Figure 2). In addition to increasing attendance-at-net rules, management authorities also need to consider strategies to minimize other sources of anthropogenic mortality in this region such as vessel strike and poor quality terrestrial runoff (Marsh *et al*., 2005).

Heinsohn *et al*. (2004) conducted a Population Viability Analysis of the remote Cape York dugong population where the indigenous harvest of dugongs is the major source of mortality and concluded that this mortality was not sustainable. Indigenous hunting is a Native Title right making it difficult for the regulatory agencies to limit catches, a situation that increases the concern about gill netting bycatch. Four locations were identified in this study where netting is still permitted and conducted in dugong management units of high or medium conservation value: the regions surrounding (1) Bathurst Head; (2) Friendly Point; and (3) Lookout Point (Figure 3). Increased protection or modified fishing practices should be considered for these regions.

## Advantage of embedding area closures in a network of MPAs

The analysis indicates that the dedicated dugong MPAs (DPAs) did not provide protection comparable to that of the ecosystem-scale network of MPAs implemented in the GBRWHA in 2004. Only 7% of the high conservation value dugong management units and 12% of the medium conservation value units that have a low risk of bycatch are within designated DPAs. Furthermore, increasing netting restrictions in DPAs Zoned B will have a minimal affect on dugong protection in the region. Thus this case study demonstrates the potential power of the over-arching design of an ecosystem-scale MPA network to protect a mobile marine mammal relative to independent small areas dedicated to protecting a single species.

The multiple-use zoning regime in the GBRWHA was designed to increase the likelihood of biodiversity conservation, sustainable fisheries, and the preservation of cultural values. It is impossible to restrict extractive activities throughout the entire GBRWHA. Nonetheless by protecting sites of high conservation value, re-zoning decreased the risk to dugongs from bycatch in commercial fisheries. It would have been difficult to expand the DPAs and restructure the Queensland East Coast Inshore Fin Fish Fishery independently of the overall re-zoning of the entire GBRWHA. Instead, dugong protection benefited from the political will to protect the entire GBR ecosystem because of its iconic and economic value both to Australians and the rest of the World. The value of the GBR is demonstrated by the region's World Heritage Listing and its annual tourism income of $A5.1 billion per annum (Access Economics, 2005).

A further benefit to the dugong population from the re-zoning of the GBRWHA was the reduction in total area where commercial trawling is permitted. Trawling does not have a direct impact on dugongs, but may alter bottom habitats and disturb dugong feeding. Dedicated dugong MPAs (DPAs) do not provide an equivalent degree of protection to dugongs because DPAs only control the distribution of commercial netting and the type of gear within their boundaries. They are not 'no take' zones as provided under the Great Barrier Reef Marin Park Zoning Plan.

## Generic implications for programmes to reduce marine mammal bycatch

The challenge of addressing the problem of bycatch of marine mammals in fisheries is complicated by the many uncertainties in existing data on marine mammal bycatch and natural systems.



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GIS-based decision support systems (DSS) such as spatial risk assessments are a potentially important addition to the tools listed by Lewison *et al.* (2004) for monitoring and evaluating interactions between marine mammals and fisheries.

GIS-based DSS and spatial risk assessments are particularly valuable in large and remote coastal regions and in the coastal waters of developing countries where there is scant scientific information on the level of bycatch and other threats to the species of concern and its ecosystem. GIS-based DSS can collate a variety of information, collected by both quantitative and qualitative methods, at a scale relevant to communities and managers. In large and remote coastal regions and in the coastal waters of developing countries, GIS-based spatial risk assessments can provide a simple, clear way of creating, communicating and analysing data from a variety of sources. Community-based GIS mapping programmes (such as Public Participatory GIS programmes involving key informants) can provide valuable qualitative information on the distributions of species and artisanal fishing effort, which can be used in association with quantitative information collected by scientists and managers in GIS-based DSS. A benefit of using information derived from such programmes is that it provides remote, regional and/or communities in developing countries with a means to participate actively in the decision-making process by contributing to the data on which decisions are made, increasing the likelihood that appropriate responses (Craig *et al.*, 2002) to marine mammal bycatch problems will be developed.

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