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Unsustainable harvest of dugongs in Torres Strait and Cape York (Australia) waters: two case studies using population viability analysis

Robert Heinsohn[1,*], Robert C. Lacy[2], David B. Lindenmayer[1], Helene Marsh[3], Donna Kwan[3] and Ivan R. Lawler[3]

[1] Centre for Resource and Environmental Studies, Australian National University, Canberra A.C.T. 0200 Australia
[2] Department of Conservation Biology, Daniel F. and Ada L. Rice Center, Chicago Zoological Society, Brookfield, IL 60513, USA
[3] School of Tropical Environment Studies and Geography, James Cook University, Douglas, Townsville, 4811and CRC Torres Strait, P.O.Box 772, Townsville 4801, Australia

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Abstract

A significant proportion of the world's remaining dugongs (*Dugong dugon*) occur off northern Australia where they face various anthropogenic impacts. Here, we investigate the viability of two dugong meta-populations under varying regimes of indigenous hunting. We construct population viability analyses (PVAs) using the computer package VORTEX and published estimates of population sizes and hunting rates. In Torres Strait between Cape York and New Guinea, our models predict severe and imminent reductions in dugong numbers. Our 'optimistic' and 'pessimistic' models suggest median times for quasi-extinction of 123 and 42 years, respectively. Extinction probabilities are also high for eastern Cape York Peninsula. We demonstrate the inadequacy of reserves when harvest rates in neighbouring areas are high, identify the maximum harvest rates for meta-population stability and emphasise the urgent need for indigenous community involvement in management to establish sustainable rates of dugong harvest in these regions.

INTRODUCTION

The dugong (*Dugong dugon*) is the only extant member of the family Dugongidae (Order Sirenia) and is listed as vulnerable to extinction by the IUCN (Hilton-Taylor, 2000). A significant proportion of the world's remaining dugongs occur off northern Australia where they face various threats (Marsh *et al*., 2002). Dugong hunting is culturally significant to both Torres Strait Islanders and Aborigines who catch the animals for meat and oil (Marsh, Gardner & Heinsohn, 1981; Smith & Marsh, 1990; Johannes & MacFarlane, 1991). South of about 16° on the east coast, there has been considerable management intervention to address anthropogenic impacts on dugongs especially in the Great Barrier Reef World Heritage Area, but dugong hunting remains mostly unregulated (Marsh *et al*., 2002). Hunting and incidental drownings in commercial fishing nets are the main impacts on dugongs in the remote areas considered here.

The Torres Strait, between Australia and Papua New Guinea, is the most important dugong habitat in the world (Marsh *et al*., 2002). Marsh *et al*. (2004) report the results of 10 surveys since 1976 of the indigenous dugong harvest in the Torres Strait Protected Zone (TSPZ), an area established to protect the traditional lifestyles of Torres Strait Islanders and which includes the three main dugong hunting communities in the Australian Islands of Torres Strait. The mean catch estimates ranged from 110–1226 animals per year. The 2 years for which both harvest and population estimates were available showed roughly similar rates of capture. In 1991 approximately 5% (1226) of 24225 (standard error (SE) = 204) dugongs were captured in the TSPZ whereas approximately 4.4% (619) of 14106 (SE = 134) dugongs were captured in 2001.

There are three major difficulties in assessing the sustainability of these apparently high rates of dugong harvest. First, four population estimates over 14 years showed large fluctuations (range = 13319–27881 dugongs) that cannot be accounted for by the effects of either harvest or intrinsic population growth alone. Marsh *et al*. (2004) concluded that large numbers of dugongs periodically move into and out of the Torres Strait, probably as a result of dieback of important seagrass beds. Thus it is difficult to determine how much of a population decrease is due to migration versus harvesting.

Second, the harvest estimates vary considerably among island communities (Marsh, Harris & Lawler, 1997) and do not account for dugongs taken in neighbouring areas including the Inner Islands, the Northern Peninsula Communities or the communities along the Papua New Guinea coast because data from these areas are not available (Marsh *et al*., 2004).

Last, we do not have any data from the Torres Strait or northern Cape York on the magnitude of other anthropogenic sources of dugong mortality, especially drowning in nets. Although the distribution and abundance

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*All correspondence to: Robert Heinsohn. Tel: 61-2-6125 2100; Fax: 61-2-6125 0757; Robert.Heinsohn@anu.edu.au

of dugongs have influenced the placement of highly protected areas in the northern Great Barrier Reef region, dugongs are not protected from incidental drowning in commercial gill nets in the hunting grounds of the Cape York communities.

The dugong meta-population in eastern Australia and New Guinea is contiguous, with potential movements over hundreds of kilometres (Marsh & Rathbun, 1990; Preen, 1995). High rates of harvest in one area may be offset by a low rate in an adjoining area. Conversely an area of low harvest may be 'bled' by neighbouring areas of high harvest. Such spatial heterogeneity ideally requires knowledge of population structure that is not currently available but which can be addressed by sophisticated analysis at the meta-population level.

In this paper, we assess the sustainability of the Torres Strait dugong fishery in a population viability analysis (PVA). PVAs are usually conducted as simulation models used to make quantitative predictions about population size over time and the likelihood of extinction and they examine the relative effectiveness of alternative management options (Beissinger & Westphal, 1998). Because some life-history variables for dugongs are either poorly known or can vary considerably, we build models for both best and worst case scenarios. We apply the same criteria to another remote area on eastern Cape York Peninsula and evaluate the likelihood of extinction for both meta-populations under varying levels of harvest. Our conclusion that current rates of harvest are unsustainable accords with Marsh *et al.* (2004) in a companion paper using the Potential Biological Removal method.

METHODS

Life-history and habitat requirements of the dugong

Most information about dugong life history has been obtained indirectly from retrieved carcasses. Females have their first calf at between 6 and 17 years of age, gestation is about 13 months and litter size is one. The mean inter-calving interval is 2.8–7 years (Kwan, 2002). The oldest individual aged from growth rings on tusks was 73 years old (Marsh, 1995). Dugongs mate polygynously and form mating herds in which males compete for females (Preen, 1989; Boyd, Lockyer & Marsh, 1999).

Dugongs have the capacity to move large distances but their movements are highly individualistic. One individual in the Gulf of Carpentaria moved 600 km over 5 days and another travelled a distance of 140 km three times over 6 weeks (Marsh & Rathbun, 1990; Preen, 1995). However, in one study of 10 dugongs, only four made substantial journeys (Preen reported in Marsh *et al.*,1999).

Study areas and sources of data

This paper draws from published data on surveys and hunting rates. Population sizes have been estimated along the entire Queensland coast using aerial surveys with corrections for perception and availability biases (see Marsh & Sinclair, 1989; Pollock *et al.*, in press).

Torres Strait

Torres Strait was surveyed for dugongs in 1987, 1991, 1996 and 2001 (Marsh *et al.*, 2004). Although the geographical distribution of dugongs was similar between surveys, the 1987 estimate (13319 ± 2136 (mean ± SE)) was less than half of that in 1996 (27881 ± 3095), and the total population had almost halved again by 2001 (14106 ± 2314). We used the largest population estimate and the survey blocks reported by Marsh *et al.* (2004). We grouped their blocks 0 (western-most coastal New Guinea) and 3 (a nominal dugong sanctuary) into our single block 1 (Fig. 1) as this area is believed to have low rates of harvest. We grouped their blocks 1B, 2A, 2B, 4, and 5 into our single block 2 as this area comprises the TSPZ for which harvesting estimates are available. Their block 1A (Daru, Papua New Guinea), which falls outside the TSPZ, becomes our block 3. To combine data from their different blocks we added the population estimates and pooled the variances to calculate new standard errors.

Eastern Cape York

The waters off eastern Cape York from Shelburne Bay to Cape Bedford (Fig. 1) were surveyed for dugongs in 1985, 1990, 1995 and 2000 and there have been no significant changes detected in the overall population over this period (Marsh & Lawler, 2002). We use the results from the 1985 survey (Marsh & Saalfeld, 1989) as these reflect the most commonly recorded distribution of dugongs, but reduce their 14 blocks to four regions that reflect the probable travelling reach of hunters in Aboriginal communities. We consider their blocks 8 and 9 to be one region (our block 5 or Lockhart River) in which the entire inshore area of the dugong population is within 70 km, and therefore within reach, of hunters from the Lockhart River Community (Fig. 1). Their blocks 10–14 (our block 4 or Cape Grenville) are probably out of reach of most Aboriginal hunters as there are no nearby communities and few access roads, although indigenous hunters from the west of Cape York and Torres Strait hunt there on occasion (Roberts, Klomp & Birckhead, 1996; M. Blackman pers. comm.). Marsh & Saalfeld's (1989) blocks 5–7 comprise our block 6 or Princess Charlotte Bay. There is a small permanent community at Port Stewart and other access roads that allow hunters into this region. We treat their blocks 1–4 from Cape Melville to Cape Bedford as one population (our block 7 or Cape Flattery). Dugongs in this region are hunted by Aboriginal people from the Hopevale Community who have to travel up to 90 km by sea (Smith & Marsh, 1990; Marsh, 2003).

Population Viability Analyses

The computer program VORTEX (Version 9.22, Lacy, Borbat & Pallak, 2003) is an individual-based simulation of the deterministic and stochastic forces affecting

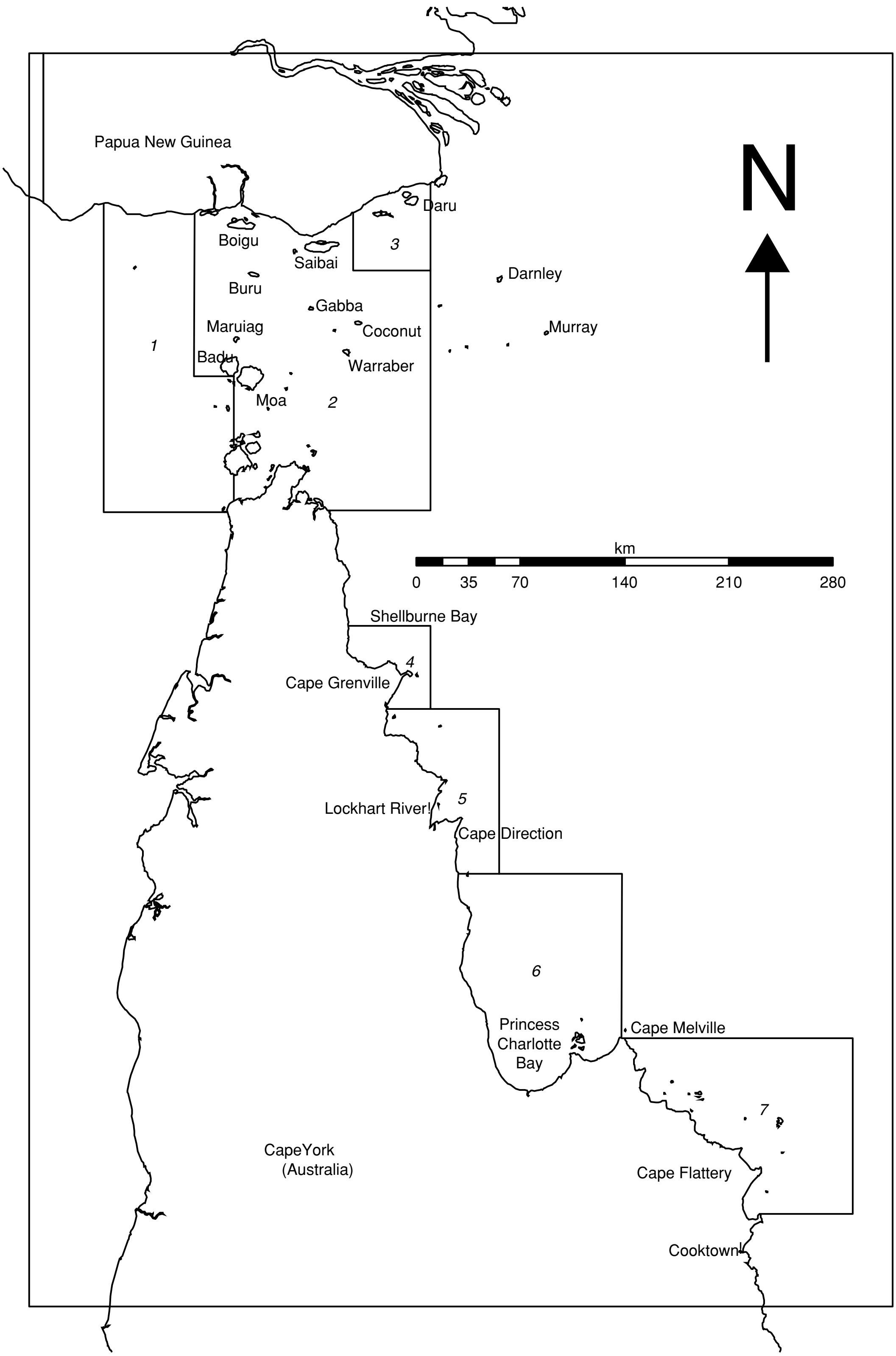

Fig. 1. Populations used in Torres Strait (1–3) and Eastern Cape York (4–7) population viability analyses (PVAs).

populations. It is primarily used to model the probability of extinction of small populations and the relative effects of differing treatments and perturbations. VORTEX has the ability to model sub-populations with complex dispersal patterns, and to include harvesting (Lacy, 2000*a*,*b*).

Table 1 shows the life-history parameters used for all simulations presented in this paper. Simulations were run 500 times (see Harris, Maguire & Shaffer, 1987), the time-frame for simulations was 200 years and 'quasi-extinction' was defined as the population reaching 10%

Table 1. The range and actual values used for all life-history parameters

Parameter	Range	Values used
Age at first reproduction for males	10–17 years	10
Age at first reproduction for females	10–17 years	10
Inter-birth interval	2.8–7 years	2.8, 6.3
Mating system	Polygynous	Polygynous
Number of young	1	1
Sex ratio of young	0.5	0.5
Annual mortality (age 0–1)	Unknown	19%
Annual mortality (age 1–2)	Unknown	8.5%
Annual mortality (age 2–4)	Unknown	3.8%
Annual mortality (age 4–10)	Unknown	2.8%
Annual mortality (adults)	Unknown	2.8%
Maximum age	73	70
Dispersing sex	Both	Both

of its original size. We examined the sensitivity of the PVAs to juvenile and adult mortality, age at first calf and the inter-calving interval. The full Vortex project files, listing all input values used in the analyses, are available at http://www2.netcom.com/~vortex/projects/dugong.zip.

In the absence of data on natural mortality we used survival data from a close relative of the dugong, the Florida manatee (*Trichechus manatus latirostris*). We used the figure of 2.8% for adult mortality derived by Langtimm & Beck (2003) from their 19 year data set in a population with low human impact and in non-hurricane years. For juveniles we used figures derived by Anon (2002) for manatees in the least human-disturbed habitats (Table 1). Marsh (1995) calculated mean (± SE) inter-birth intervals for female dugongs in three populations ranging from 2.91 ± 0.43 to 6.28 ± 1.11 years. Kwan's (2002) research on Mabuiag Island in the Torres Strait has recently shown that the mean inter-birth interval can be as low as 2.8 years.

Torres Strait PVA

Table 2 shows the sizes of the three populations used in our analysis (from Marsh *et al*., 2004). In our primary model, we assumed that dugongs were distributed according to habitat availability and allowed constant numbers to move between populations (see also the sensitivity analysis below). Thus, we initially allowed 1000 dugongs to move from population 1 to population 2 per annum and *vice versa*. Because population 3 is smaller, we allowed only 500 dugongs to move from population 2 to population 3 per annum and *vice versa*. We allowed for considerable increases in the meta-population by setting the carrying capacity at 150% of the largest known population sizes.

We built models for 13 scenarios covering varying hunting regimes in the TSPZ (population 2, see Table 3). For each hunting regime we constructed two models using inter-birth intervals of 2.8 and 6.3 years, since this life-history variable had the greatest impact on potential population growth (see Results). We modelled the viability of the meta-population when there is no hunting (Models 1 and 2), when 100 dugongs are taken per annum in population 2 (Models 3 and 4), when 250 dugongs are taken (Models 5 and 6), when 500 dugongs are taken (Models 7 and 11) and when 1000 dugongs are harvested annually (Models 12 and 13). We assumed a constant harvest when population size was large, but limited the harvest to 10% of population 2 when the population size fell to reflect the increasing difficulty of hunters in finding their prey.

Models 8, 9 and 10 use the case when 500 dugongs are harvested to explore the effect of varying rates (multipliers of 0.25, 0.5 and 1.5) of movement of dugongs between populations. Hunting was kept at the low level of 50 dugongs per annum in each of populations 1 and 3. We did not include the effects of inbreeding depression because the populations are currently large enough that substantial inbreeding is unlikely.

There is evidence that dugongs suffer severe effects from periodic dieback of the seagrass beds they require for foraging and that this may cause heightened mortality and large-scale movements such as those observed in the Torres Strait (Marsh *et al.*, 2004). All models included 'catastrophes' of this nature that struck the meta-population randomly on average every 10 years. Following Langtimm & Beck's (2003) observations for Florida manatees, each catastrophe incurred a further 9% mortality and the entire meta-population failed to breed in that year.

Eastern Cape York Peninsula PVA

Table 4 shows the population sizes recorded over four aerial surveys in the four regions comprising the Cape

Table 2. Mean population estimates (± standard error) for three regions (populations) in the Torres Strait

	Population estimate			
Population	1987	1991	1996	2001
1. West	2822 ± 1102	7436 ± 1972	9775 ± 2441	5473 ± 1327
2. Torres Strait Protected Zone	9367 ± 1809	15123 ± 2418	15679 ± 1783	7948 ± 1869
3. Daru	1131 ± 278	1669 ± 999	2427 ± 663	685 ± 317

Adapted from Marsh *et al*. (2003).

Table 3. Predictions of models 1–13 for Torres Strait, including mean annual rate of population change across the simulations (r ± SD), probability of quasi-extinction over 200 years, the mean final extant population size (± SD) and the median time (years) to quasi-extinction

Model	Description	Mean population change (r)	P-quasi-extinction	Mean extant population	Median quasi-extinction time
1	No harvested, inter-calving interval (I.C.) = 2.8	0.023 ± 0.055	0	28705 ± 1999	–
2	No harvest, I.C. = 6.3	– 0.007 ± 0.047	0.07	8565 ± 4758	–
3	Harvest = 100, I.C = 2.8	0.016 ± 0.055	0	27851 ± 2609	–
4	Harvest = 100, I.C = 6.3	– 0.026 ± 0.04	1.00	0	86
5	Harvest = 250, I.C. = 2.8	– 0.008 ± 0.055	0.07	25944 ± 4933	–
6	Harvest = 250, I.C. = 26.3	– 0.039 ± 0.050	1.00	0	59
7	Harvest = 500, I.C. = 2.8	– 0.013 ± 0.057	0.85	16185 ± 9659	123
8	Harvest = 500, I.C. = 2.8, 0.25*dispersal	– 0.007 ± 0.055	0.39	7219 ± 2986	–
9	Harvest = 500, I.C. = 2.8, 0.5*dispersal	– 0.013 ± 0.056	0.88	9730 ± 6788	129
10	Harvest = 500, I.C. = 2.8, 1.5*dispersal	– 0.014 ± 0.058	0.88	17724 ± 8661	113
11	Harvest = 500, I.C. = 6.3	– 0.054 ± 0.049	1.00	0	42
12	Harvest = 1000, I.C. = 2.8	– 0.035 ± 0.055	1.00	0	64
13	Harvest = 1000, I.C. = 6.3	– 0.069 ± 0.046	1.00	0	34

SD, standard deviation.

Table 4. The mean population sizes (± standard error) in four regions of eastern Cape York over four aerial surveys

Population	1985	1990	1995	2000
4. Cape Grenville	401 ± 121	475 ± 119	489 ± 132	595 ± 128
5. Lockhart River	745 ± 218	829 ± 305	305 ± 181	389 ± 132
6. Princess Charlotte Bay	4573 ± 833	5637 ± 1293	5072 ± 1097	2773 ± 439
7. Cape Flattery	2321 ± 637	3235 ± 838	1377 ± 283	5436 ± 784
Total	7925 ± 1068	10176 ±1575	7843 ± 1155	9081 ± 917

Data summarised from Marsh & Lawler (2000).

York meta-population. Our models used the same life-history, movement, carrying capacity and catastrophe criteria outlined for Torres Strait.

Smith & Marsh (1990) reported that 15 dugongs were harvested over a 3 month period at Lockhart River and mentioned anecdotal reports that at least six more were taken during the same period. Although the vagaries of weather and boat availability mean that annual catches cannot necessarily be extrapolated from these figures, this may indicate that over 80 dugongs were harvested in 1 year. Smith & Marsh (1990) recorded 15–27 dugongs captured per year by Hope Vale hunters between 1984 and 1987. Information sheets returned by hunters, together with estimates from the ranger, suggest that about 40 dugongs were harvested in 2001 (pers comm. to H. Marsh, 2001). Interviews with hunters suggest that the harvest in 2002 was much higher than in 2001 (M. Nursey-Bray, unpublished results).

In our models we used three levels of harvest in both the Lockhart River and Cape Flattery regions. We modelled harvests of 20, 50 and 100 dugongs to represent levels that we consider modest, realistic and extreme, respectively (see Marsh, 2003 for a discussion of harvest rates at Hope Vale). We kept harvesting in Princess Charlotte Bay (population 6) constant at 50 dugongs per year, but explored this assumption in a sensitivity analysis using harvesting rates of 20 (model 4b) and 100 dugongs per annum (model 4c). Harvesting was not allowed to go above 10% of each population to reflect the greater difficulty for hunters when dugongs become scarce. Table 5 shows the model variations.

RESULTS

Torres Strait

Table 3 shows the predictions of Models 1–13. The basic model, with no harvesting in the TSPZ, shows that a meta-population with a mean inter-birth interval of 2.8 years remains at approximately the same size over 200 years (Model 1). When the inter-birth interval was set to 6.3 years, the meta-population decreased over 200 years and had a quasi-extinction probability of 0.07 (Model 2).

When 100 dugongs are harvested annually, the meta-population stays roughly the same size when the inter-birth interval is 2.8 years, but becomes quasi-extinct in a median time of 86 years when the inter-birth interval is 6.3 years (Models 3 and 4, respectively). When 250 dugongs are harvested annually, Models 5 and 6 show that the meta-population has a quasi-extinction probability of 0.07 when the inter-birth interval is 2.8 years, but this

Table 5. Predictions of models 1–20 for eastern Cape York including mean annual rate of population change across the simulations (± SD), probability of quasi-extinction over 200 years, the mean final extant population size (± SD) and the median time (years) to quasi-extinction

Model	Lockhart harvest	Cape Flattery harvest	I.C interval	Mean population growth	P-quasi-extinction	Mean final population	Median quasi-extinction time
1	0	0	2.8	0.023 ± 0.055	0	17078 ± 1278	–
2	0	0	6.3	– 0.006 ± 0.047	0.040	3596 ± 2181	–
3	20	20	2.8	0.017 ± 0.055	0	16797 ± 1403	–
4a	20	20	6.3	– 0.030 ± 0.049	1.000	0	75
4b	20	20	6.3	– 0.022 ± 0.047	0.998	1666 (no SD)	101
4c	20	20	6.3	– 0.04 ± 0.049	1.00	0	57
5	20	50	2.8	0.014 ± 0.055	0.004	16667 ± 1731	–
6	20	50	6.3	– 0.037 ± 0.050	1.000	0	61
7	50	20	2.8	0.015 ± 0.055	0.002	16274 ± 1741	–
8	50	20	6.3	– 0.032 ± 0.048	1.000	0	72
9	50	50	2.8	0.012 ± 0.055	0.026	15927 ± 2202	–
10	50	50	6.3	– 0.04 ± 0.05	1.000	0	56
11	100	20	2.8	0.011 ± 0.055	0.002	15165 ± 2106	–
12	100	20	6.3	– 0.033 ± 0.049	1.000	0	69
13	100	50	2.8	0.008 ± 0.055	0.032	14861 ± 2630	–
14	100	50	6.3	– 0.041 ± 0.05	1.000	0	55
15	20	100	2.8	0.009 ± 0.055	0.074	15410 ± 3223	–
16	20	100	6.3	– 0.042 ± 0.049	1.000	0	54
17	50	100	2.8	0.003 ± 0.056	0.240	14185 ± 4300	–
18	50	100	6.3	– 0.046 ± 0.048	1.000	0	49
19a	100	100	2.8	– 0.001 ± 0.056	0.32	11738 ± 4889	–
19b	100	100	2.8	0.008 ± 0.055	0	14224 ± 3311	–
19c	100	100	2.8	– 0.015 ± 0.058	0.832	11806 ± 4306	97
20	100	100	6.3	– 0.047 ± 0.048	1.000	0	49

SD, standard deviation; I.C., inter-calving.

Hunting rates for Princess Charlotte Bay in all models were kept at 50 dugongs per annum (except Model 1, hunt rate = 0; Model 2, hunt rate = 0; Model 4b, hunt rate = 20; Model 4c, hunt rate = 100; Model 19b, hunt rate = 0; Model 19c, hunt rate = 100).

jumps to 1.00 with a median time to extinction of 59 years when the inter-birth interval is 6.3 years (Models 5 and 6). The remaining models show that increased harvests are associated with ever shorter median times to quasi-extinction. In the most extreme case, an annual harvest of 1000 dugongs when the inter-birth interval is 6.3 years would bring about quasi-extinction in a median time of 34 years. Because recorded harvests in the TSPZ vary between 120 and 1226 dugongs per year we suggest that the models using 500 dugongs per year best capture the current state of the population dynamics in the Torres Strait. Predicted population sizes and standard deviations for most models are given in Fig. 2.

Our sensitivity analysis shows that the probability of quasi-extinction decreases markedly (from 0.85–0.39) when the rate of dispersal between populations is decreased to one quarter the rate used in the main models (Model 8). The remaining models in the sensitivity analysis show decreasing times to quasi-extinction as the rate of dispersal between populations increases (Models 7, 9 and 10: Table 3).

The effects of changing life-history values on the deterministic population growth rate are shown in Table 6. The alternative plausible values generally yield mean population growth rates between the extremes (– 0.007%

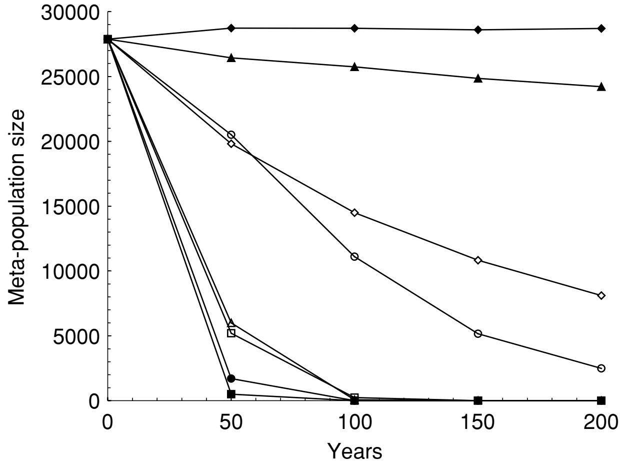

Fig. 2. Representative curves showing the predicted meta-population sizes in Torres Strait for eight population viability analysis (PVA) models. Symbols and standard deviations of predictions for each model at 50, 100, 150 and 200 years are: Model 1 (closed diamonds, 1887, 1876, 2092, 1999); Model 2 (open diamonds, 4640, 5420, 5052, 4871); Model 3 (closed triangles, 3862, 5439, 6874, 8013); Model 4 (open triangles, 3623, 213, 0, 0); Model 5 (open circles, 7192, 9930, 8509, 6812); Model 8 (closed circles, 998, 6, 0, 0); Model 9 (open squares, 2441, 285, 5,); Model 10 (closed squares, 259, 2, 0, 0).

Table 6. Changes in deterministic population growth values using differing life-history parameters

Parameter	Value	Deterministic growth rate (%)
Inter-calving interval	2 years	3.8
	2.8 years	**2.3**
	4 years	1.0
	5 years	0.2
Age at first calf	**10 years**	**2.3**
	12 years	1.9
	15 years	1.3
	17 years	1.0
Juvenile mortality	10%	2.8
	19%	**2.3**
	30%	1.8
Adult mortality	2%	2.8
	2.8%	**2.3**
	4%	1.6

Parameters for the basic model are in bold.

and 2.3%) tested in our models. Substantial decreases in both juvenile and adult mortality cause relatively modest increases in the deterministic growth rates.

Eastern Cape York

Table 5 summarises the predictions of all 20 models for eastern Cape York. The basic model with no harvesting at either of Lockhart River or Cape Flattery shows an increasing population when the inter-birth interval is 2.8 years and a decreasing population with probability of quasi-extinction of 0.04 when the inter-birth interval is 6.3 years (Models 1 and 2). The models then show that any level of harvesting across the meta-population is unsustainable when the inter-birth interval is 6.3 years, with median quasi-extinction times of 49–97 years (Models 3, 4, 6, 8, 10, 12, 14, 16, 18 and 20). The meta-population has a high probability of quasi-extinction ($P = 0.998$) even when harvesting in Princess Charlotte Bay is reduced to 20 dugongs per year and harvesting elsewhere is kept low (Model 4b).

When the meta-population is modelled with an inter-birth interval of 2.8 years, the probability of quasi-extinction is zero when 20 dugongs are harvested at both Lockhart River and Cape Flattery (Model 3), 0.026 when 50 dugongs are taken at both places (Model 9) and rises to 0.32 when 100 dugongs are taken at both localities (Model 19a). In the latter case, our sensitivity analysis shows that the probability of extinction decreases to zero when harvesting is reduced at Princess Charlotte Bay, but increases to 0.832 when it is increased to 100 dugongs at that locality. Representative curves for the predictions of Models 1–20 are shown in Fig. 3.

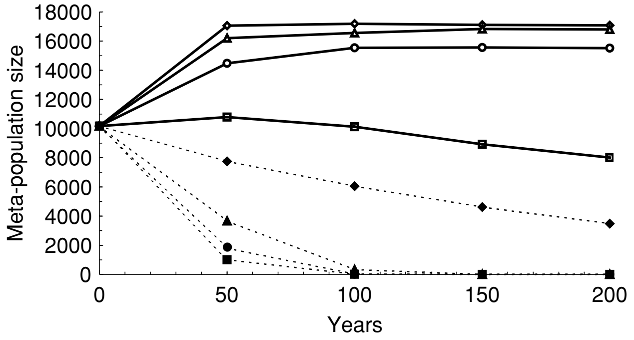

Fig. 3. Representative curves showing the predicted eastern Cape York meta-population sizes for eight population viability analysis (PVA) models. Symbols and standard deviations for each model at 50, 100, 150 and 200 years are: Model 1 (open diamonds, 1223, 1152, 1235, 1278); Model 2 (closed diamonds, 2322, 2666, 2417, 2207); Model 3 (open triangles, 2173, 1786, 1545, 1403); Model 4 (closed triangles, 1705, 663, 22, 0); Model 9 (open circles, 3205, 3120, 3159, 3318); Model 10 (closed circles, 1123, 52, 0, 0); Model 19a (open squares, 4043, 5516, 6367, 6771); Model 20 (closed squares, 637, 10, 0, 0).

DISCUSSION

The results of our PVA confirm the contention of Marsh *et al.* (1997, 2004) that dugongs in the Torres Strait are being harvested in an unsustainable manner. At a harvest rate of 500 dugongs per year, numbers will have fallen to less than 10% of their 1996 levels in a median time of between 42 and 123 years. Our models for eastern Cape York Peninsula also predict potentially dire consequences if harvesting rates are not kept below about 20 dugongs per year in each of the Lockhart River and Cape Flattery regions. Here, we discuss the validity of our models and suggest management options for preserving dugong numbers in Torres Strait and Cape York waters. We stress that our aim is not to be critical of the rights of indigenous people to hunt dugongs. Rather, we aim to identify and help rectify a current problem so that dugongs can persist in healthy numbers in northern Australia, so that indigenous people have the option to continue to hunt them in the near and distant future.

Our PVA models provide both optimistic and pessimistic predictions by using the highest and lowest known values of the most sensitive life-history parameter, the inter-birth interval (Kwan, 2002). Although wildlife managers should err on the side of caution, both approaches provide useful information. When even optimistic models show a high probability of quasi-extinction, harvesting can be considered unsustainable with a high degree of confidence. We draw attention to six factors that affect the conclusions that can be drawn from our models.

First, the efficacy of aerial surveys to provide accurate estimates of population size has recently been verified experimentally by Pollock *et al.* (in press). This also leads to greater confidence that the large fluctuations in dugong numbers seen in Torres Strait since 1987 are not due to survey inadequacies. Marsh *et al.* (2004) have concluded that dugongs move in large numbers into and out of the survey area. Our analysis confirms that the dramatic decrease in Torres Strait dugong numbers between 1996 and 2001 (from 27881 to 14106) could not have been due to harvesting alone. Even in our worst case scenario (inter-birth interval 6.3 years, 1000 dugongs harvested annually), the mean population decrease over a 5 year period would have been, at most, 3000 animals (Fig. 2). Marsh *et al.* (2004) have emphasised that aerial surveys over the short term are less effective at identifying population trends, leaving tools such as PVA as the best method. However, aerial surveys remain vital for validating longer term population changes and for improving estimates of dugong movements within the metapopulations.

Second, our models include the catastrophic effects of large scale seagrass dieback events. Episodic dieback of hundreds of kilometres of seagrass beds have been recorded in association with extreme weather events such as cyclones and floods that cause increased turbidity and inadequate light environments for seagrass growth (Johannes & MacFarlane, 1991; Preen *et al.*, 1995; Poiner & Peterkin, 1996). The effect of such dieback on dugongs is twofold. Some remain in the area but lose body condition, delay breeding and suffer increased mortality, while others move hundreds of kilometres with unknown consequences (Preen & Marsh, 1995; Marsh *et al.*, 1996). Our models include catastrophic events that occur every 10 years on average (the apparent time-frame over the four aerial surveys) and that have mortality and fecundity effects of the magnitude recorded for Florida manatees after hurricanes (Langtimm & Beck, 2003).

Third, our analysis suggests that even large reserves will have limited effect in protecting local populations if harvests are high in neighbouring areas. When harvesting is high in some areas, higher mobility of dugongs between populations increases the probability of quasi-extinction for the meta-population. The rates of inter-population movement used in our analyses are potentially conservative (e.g. Preen, 1995) and may underestimate the effect of areas of high harvest ‘bleeding’ neighbouring areas of lower harvest.

Fourth, Marsh *et al.* (1997) observed that dugongs and the more abundant turtles are often hunted together from the same boat. Thus, search effort by indigenous people probably remains high regardless of dugong rarity. This differs from some models of hunting in which search effort decreases as prey becomes scarcer and harder to catch (Bomford & Caughley, 1996). Our models are conservative as they limit the upper harvest of any one population to reflect likely satiation of hunters, but if populations decrease considerably, harvests remain at a set percentage to reflect the greater difficulty of finding prey.

Fifth, our models assume that hunting does not occur in population 1 (a declared sanctuary) in Torres Strait and in population 4 on eastern Cape York. However, hunting probably does occur in both places (Roberts *et al.*, 1996; Marsh *et al.*, 1997; M. Blackman, pers. comm.). We also note that ‘counts’ may underestimate the true rate of harvesting at various communities and that harvest rates along the Papua New Guinea coast may have been underestimated. We ran all simulations using the maximum recorded meta-population size of 27881 dugongs as these are probably all present in the Torres Strait system at least some of the time. Although some dugongs clearly leave on occasion, and this may afford them some protection from hunting, anecdotal evidence suggests they are also at risk of being hunted elsewhere (Marsh *et al.*, 2004).

Finally, we did not make any allowance for other impacts on dugongs in this area, particularly the effect of incidental drownings in fishing nets off Cape York (Marsh *et al.*, 2002; Marsh, 2003) and habitat displacement as a result of boat traffic in Torres Strait (D. Kwan, H. Marsh & S. Delean, unpublished results). For example, in PVAs of Florida manatees, growing human populations and probable increases in boat strikes, development, pollution and degradation of the habitat were incorporated as declining trends in carrying capacity and survival rates (Anon, 2002). In northern Australia, growing human populations (Australian Bureau of Statistics, 1998) and increased access to motor boats in indigenous communities might have similar effects (Smith & Marsh, 1990; D. Kwan, H. Marsh & S. Delean, unpublished results).

Our models highlight the need for immediate action to prevent the functional extinction of dugongs in the Torres Strait. The life history of dugongs, with low fecundity and slow development, does not provide the necessary potential population growth to sustain large harvests and sanctuaries are unlikely to be effective when harvesting rates elsewhere remain high. We urge a target reduction of harvesting to no more than 100 dugongs per annum in the Torres Strait, bearing in mind that even these rates of harvest entail a high risk of quasi-extinction if the dugongs breed at the slower rate used in our models. This is similar to the sustainable harvest estimated by Marsh *et al.* (2004) using the Potential Biological Removal technique (Wade, 1998).

Dugongs may be similarly endangered off Cape York Peninsula but this can only be verified with further research such as Kwan’s (2002) study of life-history variables and harvest rates at all dugong-hunting communities. Until better data are available, we suggest that harvests at each of the Cape York communities be kept at less than 20 dugongs per year as recommended by Marsh (2003) for Hope Vale and prescribed in the ‘*A Guugu Yimithirr Bama Wii – Girrbithi and Ngawiya – A Turtle and Dugong Hunting Management Plan*’ (HVAC, 1999).

Many scientists have raised concerns about the sustainability of the Australian dugong fisheries (e.g. Johannes & MacFarlane, 1991; Marsh *et al.*, 1997), and government agencies such as the Australian Fisheries Management Authority have sponsored research aimed at identifying the extent of the problem and social and educational programs as possible solutions. Our results and those of Marsh *et al.* (2004) confirm that dugongs continue to be drastically over-harvested in the Torres Strait and that this may also be true in northern Cape York waters. Our analyses emphasise the urgency of the situation and we hope they will add renewed impetus to new and existing programs aimed at reducing the harvests to sustainable levels.

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