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www.publish.csiro.au/journals/wr *Wildlife Research*, 2003, **30**, 397–409

Distribution and abundance of dugongs in Moreton Bay, Queensland, Australia

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Abstract. Dugong abundances in Moreton Bay (south-east Queensland) were estimated during six bi-monthly aerial surveys throughout 1995. Sampling intensity ranged between 20 and 80% for different sampling zones within the Bay, with a mean intensity of 40.5%. Population estimates for dugongs were corrected for perception bias (the proportion of animals visible in the transect that were missed by observers), and standardised for availability bias (the proportion of animals that were invisible due to water turbidity) with survey and species-specific correction factors. Population estimates for dugongs in Moreton Bay ranged from 503 ± 64 (s.e.) in July to 1019 ± 166 in January. The highest uncorrected count was 857 dugongs in December. This is greater than previous population estimates, suggesting that either previous surveys have underestimated abundance and/or that this population may have increased through recruitment, immigration, or a combination of both. The high degree of variation in population estimates between surveys may be due to temporal differences in distribution and herding behaviour. In winter, dugongs were found in smaller herds and were dispersed over a wider area than in summer. The Eastern Banks region of the bay supported 80–98% of the dugong population at any one time. Within this region, there were several dugong ‘hot spots’ that were visited repeatedly by large herds. These ‘hot spots’ contained seagrass communities that were dominated by species that dugongs prefer to eat. The waters of Rous Channel, South Passage and nearby oceanic waters are also frequently inhabited by dugongs in the winter months. Dugongs in other parts of Moreton Bay were at much lower densities than on the Eastern Banks.

Introduction

The dugong, *Dugong dugon*, is listed as vulnerable to extinction by the World Conservation Union (IUCN 1990). Over the past century, populations of the dugong have shown marked declines throughout its Indo-Pacific range, with the notable exception of northern Australia. However, recent surveys have shown that this decline is now occurring in eastern Australia (Marsh *et al.* 1996). These population declines have been attributed to habitat loss (both natural and anthropogenic), incidental mortality in nets and traditional hunting (Marsh *et al.* 1996).

Moreton Bay supports the largest dugong population in close proximity to a major and rapidly expanding city, Brisbane (Heinsohn *et al.* 1978; Preen *et al.* 1992). This population is geographically isolated from the closest population, situated in Hervey Bay, 200 km to the north. Aerial surveys of this population have been conducted at irregular intervals since 1977 (Heinsohn 1977; Lear 1977; Heinsohn and Marsh 1980; Marsh *et al.* 1990; Preen 1993). The methodology of these surveys has not been consistent so that comparisons between them are problematic. On the basis of a strip transect survey of Moreton Bay in June 1985, Marsh *et al.* (1990) estimated the population to be 458 ± 78 (s.e.) dugongs. Between July 1988 and February 1990, Preen (1993) conducted 28 ‘standard’ surveys of central Moreton Bay (which comprises the major dugong habitat) and concluded that the bay supported 500–569 dugongs year round. By April 1993 this population estimate had increased to ~664 dugongs, possibly through immigration by dugongs from Hervey Bay (Preen and Marsh 1995), making it one of the largest dugong populations remaining on the Queensland coast south of Cape York (Marsh *et al.* 1996).

The present series of aerial surveys follows the recent detection of major dugong population declines further north in Hervey Bay (Preen and Marsh 1995; Preen *et al.* 1995) and in the southern Great Barrier Reef region (Marsh *et al.* 1996). The aim of these surveys was to determine whether Moreton Bay had experienced population declines similar to those occurring elsewhere in Queensland waters. To establish a solid baseline dataset for ongoing monitoring of this population, the entire bay was surveyed under a spatially and temporally intensive regime, as recommended by Marsh

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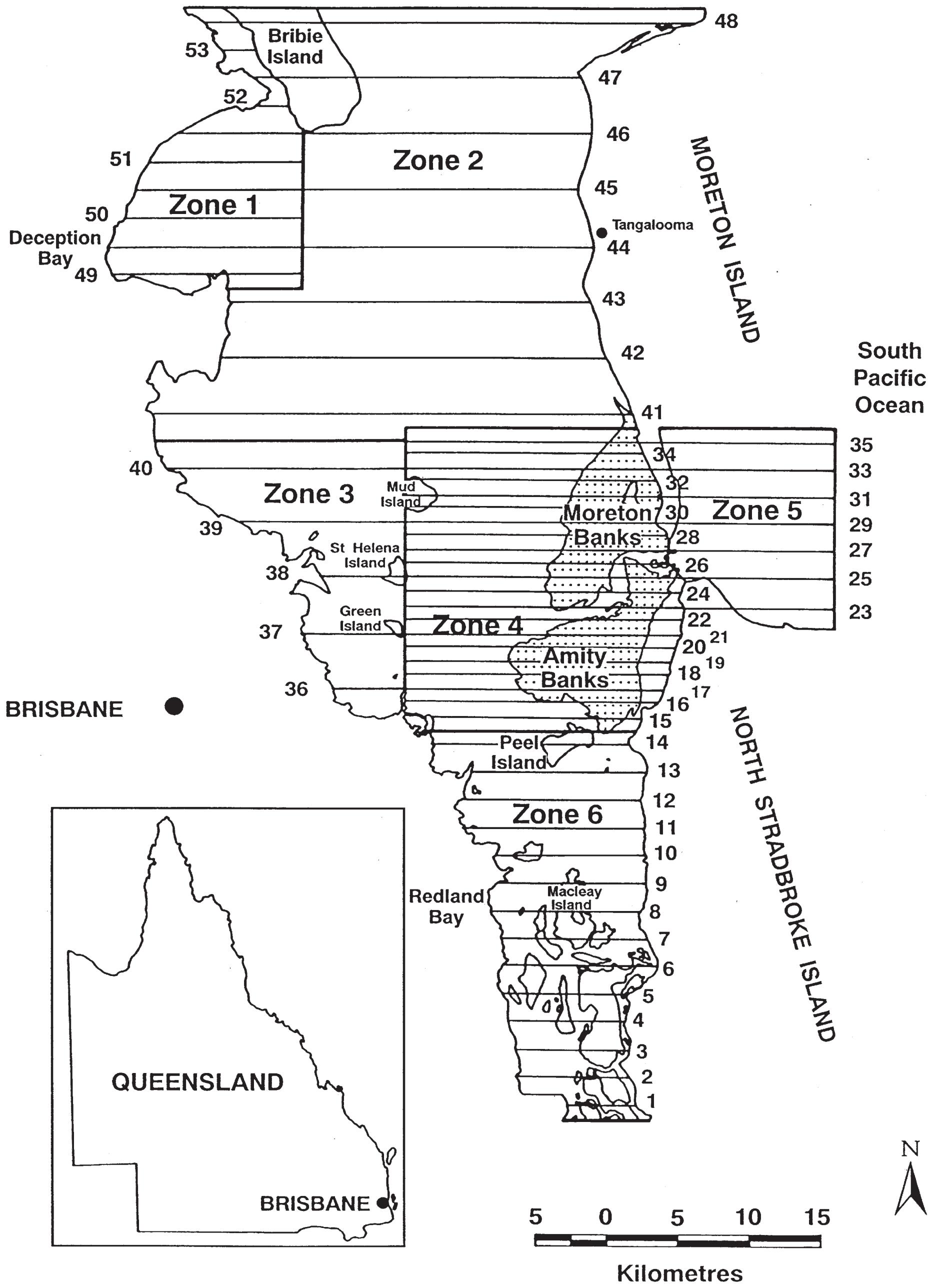

Fig. 1. 'Regular' aerial survey design of Moreton Bay: Transects 1–53 in Zones 1–6. Stippled areas are islands lying within the survey zone.

et al. (1993). These regularly repeated surveys incorporated an investigation of temporal utilisation of bay habitats by dugongs.

Methods

Study site

Moreton Bay, south-east Queensland (27.5°S, 153.3°E) is a shallow embayment protected by Moreton and North Stradbroke Islands to the east (Fig. 1). The southern part of the Bay is shallow (<10 m) with muddy sediments and contains numerous islands while the northern bay is more open. The central-eastern bay contains extensive sandbanks between, and to the west of, Moreton and North Stradbroke Islands. These shallow (<5 m at high tide) sandbanks cover an area of 110.5 km^2 and support extensive seagrass meadows (Preen 1993). Rous Channel runs roughly north-east to south-west through these sandbanks, dividing them into the northern Moreton Banks and southern Amity Banks. This 10-m-deep channel opens to the South Pacific Ocean through South Passage, between Moreton and North Stradbroke Islands (Fig. 1). The bay is adjacent to the fastest-growing major urban area in Australia (Brisbane–Gold Coast) and is heavily used by recreational anglers, commercial fishermen and maritime transport (Quinn 1993; Australian Bureau of Statistics 1998).

Survey design

For estimation of local densities of dugongs, Moreton Bay was divided into six zones based on broad habitat type and known dugong distributions (Fig. 1). The entire bay and the South Passage region

Table 1. Area of survey zones, transect coverage, perpendicular zone length and resultant survey sampling intensities for the 1995 aerial surveys of Moreton Bay

For the January survey, transect areas and resultant sampling intensities (transect area as a percentage of total zone area) for Zones 3, 4 and 6 were less than for subsequent surveys. Preen's January survey design lay within Zone 4 but did not cover the whole of Zone 4. Total zone area excludes islands

	Total area (km^2)	Transect area (km^2)	Perpendicular zone length (km)	Sampling intensity (%)
Zone 1	161.4	69.0	20.0	42.8
Zone 2	731.6	152.9	30.0	20.9
Zone 3	175.3	35.6	21.0	20.3
Zone 3 (January)	175.3	30.9	21.0	17.6
Zone 4	393.7	311.5	22.0	79.1
Zone 4 (January)	393.7	145.9	22.0	37.1
Zone 4 (Preen)	154.5	80.1	19.6	51.8
Zone 5	144.2	64.6	14.5	44.8
Zone 6	231.8	111.0	28.0	47.9
Zone 6 (January)	231.8	74.7	28.0	32.2
Total (Moreton Bay)	1838.0	744.6		40.5
Total (January)	1838.0	538.0		29.3

(Zones 1–6) were covered by 53 non-overlapping strip transects orientated east–west and spaced at intervals of 4, 2 or 1 km, corresponding to sampling intensities of close to 20%, 40% and 80% respectively (Fig. 1, Table 1). Sampling intensities were greatest over known dugong–seagrass areas (Zones 4 and 5) where transects were almost contiguous. In effect, the only area missed in Zone 4 was a strip (~100 m wide) directly below the plane. This high sampling intensity increased the likelihood of sighting most dugong herds (>10 animals) so that the count in Zone 4 closely approached a 'total census count'. Zone areas were estimated from maps generated by ArcView® GIS software.

Aerial surveys were flown at two-monthly intervals from January to December 1995. Each survey comprised approximately 8 h transect time and was flown at high tide over two 4-h sessions, on consecutive mornings where possible. The main dugong areas (Zones 4 and 5) were flown on one morning and the remainder of the Bay on the next. Surveys were conducted only when weather conditions were excellent (fair weather, cloud cover ≤4 oktas, winds ≤10–15 knots and a Beaufort sea-state ≤3). Surveys were flown in mid-morning to avoid glare and to take advantage of generally light winds. Since sightability of dugongs is facilitated when they are in clear shallow waters, surveys were flown at high tide when the shallow eastern sandbanks were accessible. However, flying at high tide each time introduced a bias in that only high-tide distributions were documented.

Survey methodology

These surveys used a slightly modified methodology to that used in other dugong surveys (Marsh and Saalfeld 1989*a*, 1989*b*; Marsh and Sinclair 1989*a*, 1989*b*; Marsh 1995). A Partenavia 68B six-seater high-wing aircraft was flown at an altitude of 274 m (rather than 137 m) at a constant ground speed of 185 km h^{-1} (100 knots). Precise navigation along transects was achieved with a Global Positioning System (GPS) in combination with visual navigation using fixed beacons and landmarks.

A strip transect width of 400 m on either side of the aircraft was demarcated using fibreglass rods attached to wing struts (Marsh 1995). Sightings were recorded as falling within the low, mid or high third of the strip transect, relative to the plane, to help to decide whether simultaneous sightings by tandem observers were of the same animal(s). The survey crew comprised the pilot-navigator, survey leader/data recorder and four observers organised as two tandem teams. As far as possible the same survey crew was used for each survey. The mid-seat observers always had at least two surveys' experience. Less-experienced observers were positioned in the rear seat and underwent 'training transects'. The same pilot flew on all but two survey days (i.e. 13 out of 15 days), and flew all flights over Zones 4 and 5. Counting procedures and data recording followed Marsh and Saalfeld (1989*a*) and Marsh *et al.* (1994). Observers recorded, in order of priority, the numbers of dugongs (including calves), dolphins, sea turtles, sharks, rays, whales and vessels, as well as sighting conditions. Sightings of vessels and animals other than dugongs have been reported elsewhere (Lanyon and Morrice 1997).

To cope with the likelihood that a high proportion of dugongs would be aggregated in large herds within Zone 4, a census count was attempted in this zone. Locations of dugong herds were recorded using a GPS. All dugongs forming part of a herd and lying within transect were counted *en route*. Herds were revisited at the end of the transect and circled at a height of 400 m until every animal was counted. Herds were also photographed for verification of herd size and composition. In addition, herds that were spotted off transect (including herds that extended into the area under the plane) were recorded and revisited for counts. Since a strip approximately 50 m below the transect was visible and herds within this were included, the 'invisible' strip under the plane was effectively reduced from ~210 m down to ~100 m. Therefore, although non-herd dugongs were sampled at an intensity of 79% in Zone 4, sampling intensity for herds was probably >90%, which was considered close enough to total census.

To minimise the likelihood of spatial auto-correlation within Zones 4 and 5, i.e. where transects lay close together, all transects within these zones were flown serially over one morning so that maximum time elapsed between adjacent transect points was short (5–6 min), effectively minimising time for dugongs to move from one transect to the next. Also, the survey leader kept a record of dugong group positions, particularly those high in transect, so that any overlap in sightings could be detected. Since auto-correlation was unlikely to be a problem with this survey design (Gordon Smyth, University of Queensland, personal communication), transects were considered to be independent sampling units.

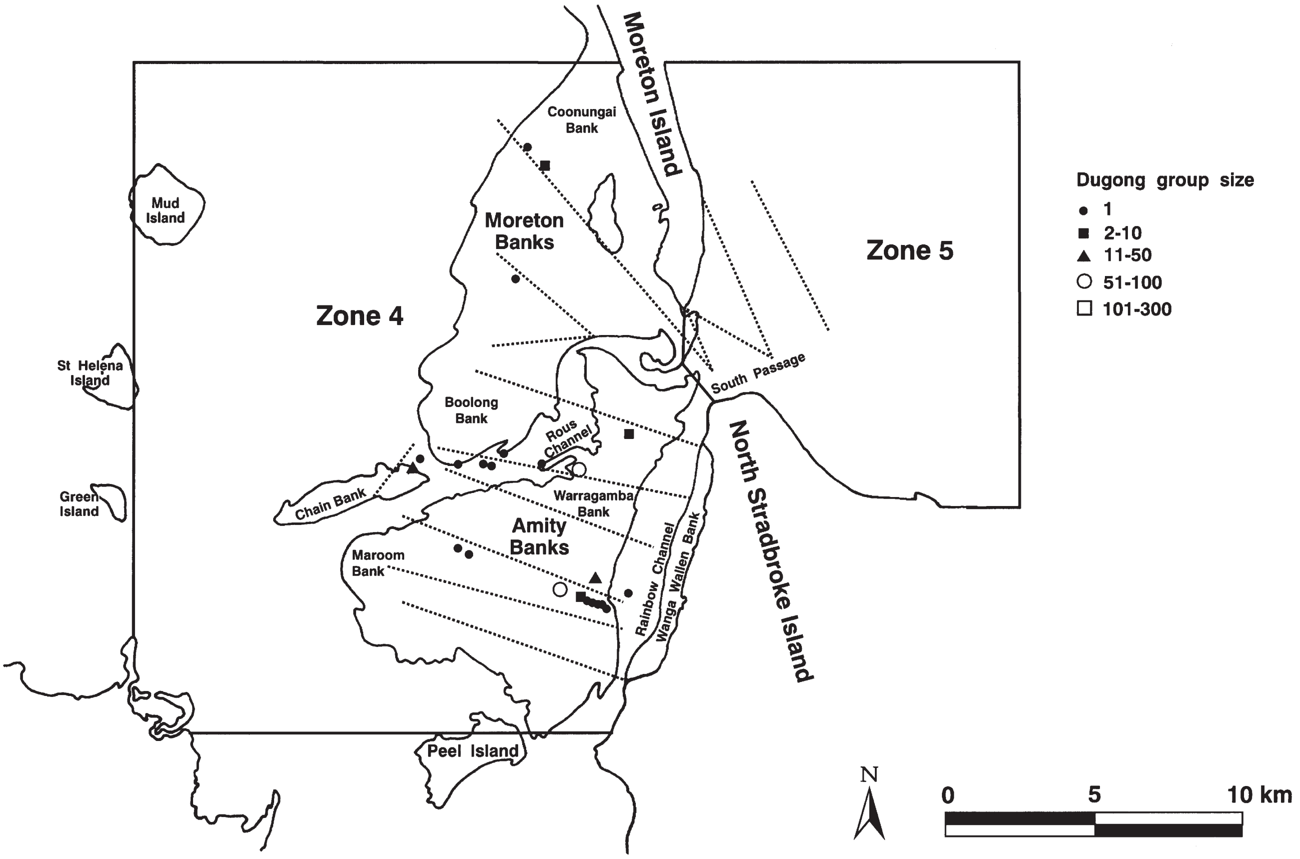

Fig. 2. 'Preen survey design' showing dugong distribution and abundance in Zones 4 and 5 in January 1995. Preen's transect lines are shown as dotted lines. Note: as in Preen's (1993) survey method, observations continued on the banking turns between transects: the tracks of these turns are not included on this map. Projection: Universal Transverse Mercator.

'Preen' survey design

A second survey pattern, Preen's (1993) 'standard' survey, was also flown in January, to compare counts obtained using Preen's survey design. This pattern (hereafter referred to as the 'Preen' design) consisted of a series of 14 transects of infinite width orientated roughly south-west to north-east and extending across the eastern banks region (Fig. 2). All of these transects were within Zone 4 of the regular survey design. This survey was flown on a mid-morning high tide in January. Modifications to the original 'Preen' survey methodology (Preen 1993) included the use of four observers plus survey leader, rather than two observers including survey leader, and recording observations onto audio tape rather than manually recording sightings onto a map.

Correction factors

Perception correction factors (PCF) (to correct for dugongs visible in the transect that were missed by the observers) and availability correction factors (ACF) (to correct for dugongs that were unavailable to observers, e.g. because of water turbidity) were calculated using the methods of Marsh and Sinclair (1989*a*). PCFs were calculated for one (specified) or both members of each tandem observer team (port and starboard), depending on the observer's level of experience, for each survey day. ACFs were calculated for each separate survey time.

ACFs for dugongs were calculated by standardising the proportion of dugongs sighted during the survey to the number seen on the surface in clear water where all dugongs were potentially available, i.e. the corrections for availability bias make an assumption that a constant proportion of the population is at the surface and visible. This constant (p_s = 0.166 or 16.6%) was originally derived from experiments conducted in the clear waters of Moreton Bay (Marsh and Sinclair 1989*b*). This ACF standard was applied across all zones except Zone 4 at some times. During some surveys, a relatively greater proportion of dugongs was seen below the surface in Zone 4 ($p_u \leq 0.166$) so that the resultant ACF correction factor (p_u/p_s) was <1.0. Applying this correction factor would have resulted in a population estimate for Zone 4 that was less than the actual number of dugongs observed. In these cases, ACF was set at a minimum of 1.0.

Data analysis

Data handling and analysis techniques were generally similar to those used in the surveys of Marsh and Saalfeld (1989*a*, 1989*b*, 1990) and Marsh and Sinclair (1989*a*, 1989*b*). Survey data were analysed using an Access® data program incorporating formulae for finite population estimation given in Marsh and Sinclair (1989*a*, 1989*b*).

Since the transects varied in area, the Ratio Method (Jolly 1969; Caughley and Grigg 1981) was used to estimate the density, population size and associated standard errors for each zone and for each survey. The standard errors of the population estimates of dugongs were corrected for the sampling fraction and adjusted to incorporate errors associated with correction factors (Marsh and Sinclair 1989*a*). Transect and zone areas were corrected to exclude areas of islands. To avoid over-estimation of dugong densities per zone, herds (>10 dugongs) were stratified out prior to calculating background density (Marsh and

Table 2. Dugong population estimates (±s.e.) (from corrected population numbers, including herds) for each zone and survey

‘Total Population’ refers to population for the entire Moreton Bay (Zones 1–6 inclusive) for each survey. ‘No. of dugongs sighted’ refers to raw numbers of dugongs sighted on transect without correction factors (nos of calves are shown in parentheses)

Flight dates	January 31.i.1995 & 2.11.1995	March 31.iii.1995 & 1.iv.1995	May 30.v.1995 & 1–2.vi.1995	July 27–28.vii.1995	September 27–29.ix.1995	December 7–8.xii.1995
Zone 1	0	3 (2.93)	2 (2.30)	11 (8.66)	0	24.68 (15.50)
Zone 2	31 (27.03)	0	6 (4.04)	6 (4.04)	6 (3.76)	9.57 (8.52)
Zone 3	47 (51.00)	0	0	0	6 (5.87)	5 (5.09)
Zone 4	757 (32.18)	571 (21.35)	353 (15.49)	195 (11.44)	921 (20.39)	921 (35.21)
Zone 5	0	0	237 (86.00)	167 (11.04)	0	0
Zone 6	184 (152.02)	31 (15.44)	0	122 (61.03)	13 (7.37)	22 (20.80)
Total population	1019 (165.99)	605 (26.51)	598 (87.74)	503 (64.27)	946 (22.77)	977 (45.55)
No. of dugongs sighted (calves)	630 (26)	524 (18)	369 (22)	347 (10)	758 (7)	857 (21)

Table 3. Group size estimates and correction factors used in population estimates of dugongs for each zone and survey time
Mean group size (MGS) of dugongs excludes herds. Perception correction factors (PCF) were calculated separately for each observer team (port and starboard) for each survey time. PCF = 1 (0) when there was only one experienced observer. Availability correction factors (ACF) were calculated for each month separately. c.v. = coefficient of variation

Survey month	Zone	Day	MGS (c.v.) (excl. herds)	No. of observers		PCF (c.v.)		ACF (c.v.)
				Port	Starboard	Port	Starboard	
January	2	2	1.00	2	2	1.45 (0.22)	1.04 (0.02)	6.00 (0.10)
	3	1	1.00	2	2	1.45 (0.22)	1.04 (0.02)	6.00 (0.10)
	4	1	1.89 (0.21)	2	2	1.45 (0.22)	1.04 (0.02)	6.00 (0.10)
	4	2	1.89 (0.21)	2	2	1.45 (0.22)	1.04 (0.02)	6.00 (0.10)
	6	1	2.29 (0.33)	2	2	1.00	1.04 (0.02)	2.40 (0.40)
	6	1	2.29 (0.33)	2	2	1.45 (0.22)	1.04 (0.02)	2.40 (0.40)
March	1	2	1.00	1	2	1.00	1.22 (0.02)	1.00
	4	1	1.75 (0.13)	2	1	1.06 (0.02)	1.00	1.02 (0.26)
	4	1	1.75 (0.13)	2	2	1.06 (0.02)	1.22 (0.02)	1.02 (0.26)
	6	2	1.00	1	2	1.00	1.22 (0.02)	4.00 (0.42)
May	1	3	1.00	2	2	1.07 (0.03)	1.08 (0.02)	1.00
	2	3	1.00	2	2	1.07 (0.03)	1.08 (0.02)	1.00
	4	2	1.55 (0.10)	1	2	1.00	1.08 (0.02)	1.00
	4	2	1.55 (0.10)	2	2	1.07 (0.03)	1.08 (0.02)	1.00
	5	2	3.00 (0.34)	1	2	1.00	1.08 (0.02)	2.50 (0.36)
	5	2	3.00 (0.34)	2	2	1.07 (0.03)	1.08 (0.02)	2.50 (0.36)
July	1	2	1.00	2	2	1.07 (0.05)	1.09 (0.05)	3.00 (0.71)
	2	2	1.00	2	2	1.07 (0.05)	1.09 (0.05)	1.00
	4	1	1.67 (0.14)	2	2	1.05 (0.04)	1.09 (0.05)	1.00
	5	1	1.00	2	2	1.05 (0.04)	1.09 (0.05)	1.00
	6	2	1.50 (0.25)	2	2	1.07 (0.05)	1.09 (0.05)	4.50 (0.20)
September	2	3	1.00	2	2	1.11 (0.02)	1.11 (0.02)	1.00
	3	2	1.00	1	1	1.00	1.00	1.00
	3	2	1.00	2	2	1.05 (0.02)	1.03 (0.02)	1.00
	4	2	1.76 (0.08)	1	1	1.00	1.00	1.00
	4	2	1.76 (0.08)	2	1	1.05 (0.02)	1.00	1.00
	4	2	1.76 (0.08)	2	2	1.05 (0.02)	1.03 (0.02)	1.00
	6	1	1.20 (0.17)	2	2	1.05 (0.02)	1.03 (0.02)	1.00
December	1	1	1.00	1	1	1.00	1.00	3.00 (0.71)
	2	1	2.00	1	1	1.00	1.00	1.00
	3	1	1.00	1	1	1.00	1.00	1.00
	4	2	1.89 (0.10)	1	2	1.00	1.04 (0.01)	1.00
	4	2	1.89 (0.10)	2	2	1.10 (0.02)	1.04 (0.01)	1.00
	6	11	1.00	1	1	1.00	1.00	3.00 (0.71)

Sinclair 1989*a*). Herds were added later to produce population and density estimates per zone (Norton-Griffiths 1978). The corrected population estimates for zones other than Zone 4 are likely to be underestimates as correction factors for the number of animals unavailable to observers due to water turbidity are probably conservative (after Marsh and Sinclair 1989*a*, 1989*b*). These population estimates are standard minimum estimates, rather than absolute estimates (after Marsh and Sinclair 1989*a*, 1989*b*).

Differences in the densities of dugongs between surveys and zones were tested using two-way analysis of variance, with and without Beaufort Sea State as a covariate. To include all herds in sampling units (transect) within Zones 4 and 5, each herd (including those lying wholly within transect, those outside but not in adjacent transect, and those extending off transect) was allocated 50% to the transect with which it was primarily associated and 50% to the adjacent transect. Data were log(x+1) transformed prior to analysis. Transects were treated as independent sampling units: the position of the first transect within each zone was determined randomly, then transects were systematically placed within zone. Although the same transects were flown on each survey to mitigate the logistic difficulty involved in flying different random transects each time, the mobility of dugongs between surveys meant that the assumption of independence for ANOVA was not compromised. Dugong distribution maps were produced using ArcView® GIS software.

Results

Population and density estimates

The total number of dugongs sighted on transect for all of Moreton Bay ranged from 347 in July to 857 in December. Corrected population estimates for Moreton Bay ranged from 503 ± 64 (s.e.) in July to 1019 ± 166 (s.e.) in January (Table 2). Dugong population estimates decreased over the first four surveys (January through July) with the lowest population estimates occurring in the winter months (Table 2). Population estimates were higher and less variable

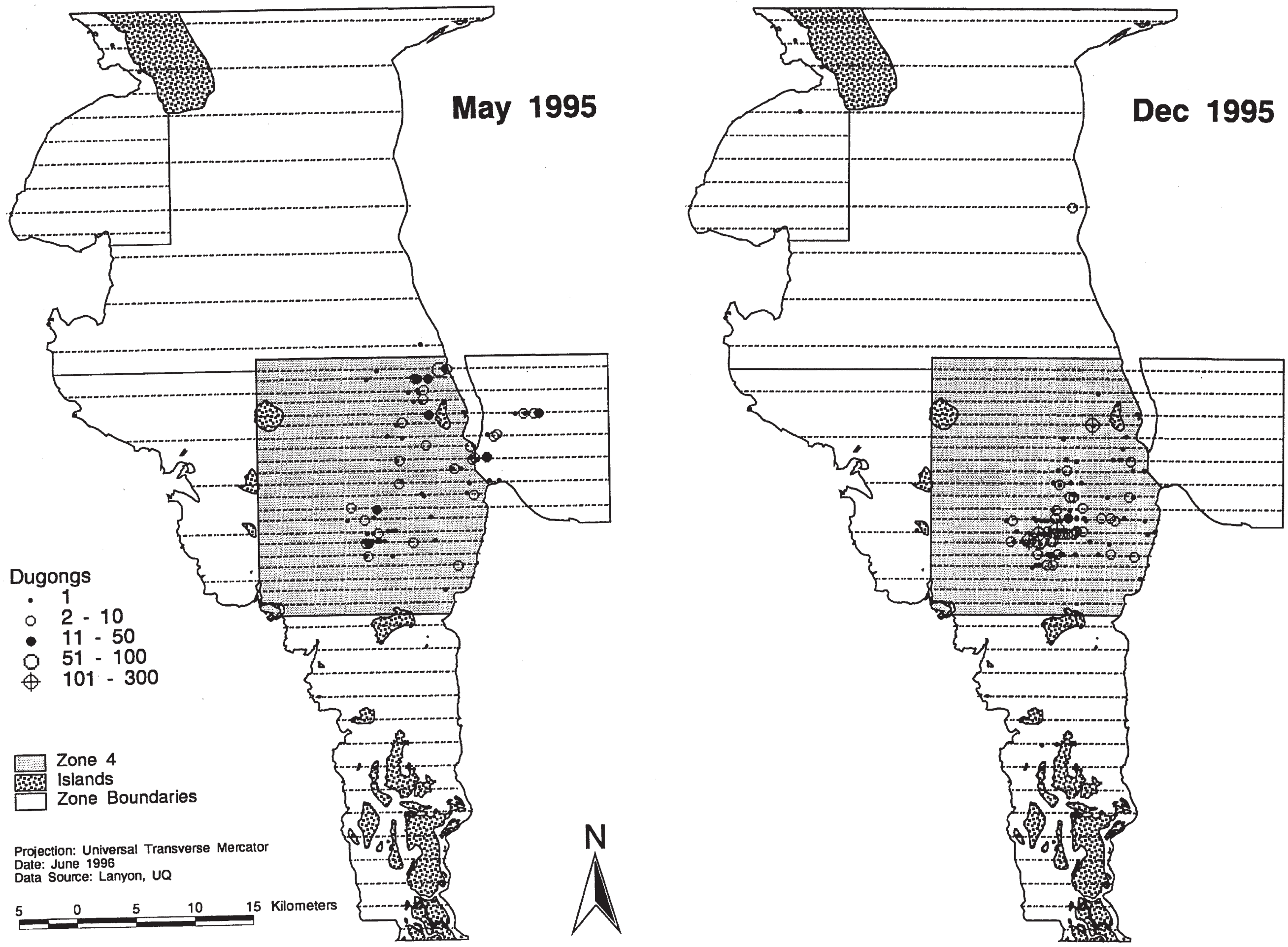

Fig. 3. Dugong distribution and abundance in Moreton Bay at two survey times: May and December 1995. Dotted lines represent transect lines; solid lines are boundaries between zones. Projection: Universal Transverse Mercator.

in the January, September and December surveys. The mean group sizes and the correction factors used to calculate population and density estimates for each survey are given in Table 3.

There was a significant time by zone interaction ($F = 1.96$, d.f. = 25, $P = 0.046$), indicating that temporal trends in dugong densities were different in different zones. In all surveys, most dugongs (80–98% of the estimated population) were associated with the seagrass beds on the eastern banks, i.e. Zone 4 (Table 2; Fig. 3). In May and July, substantial proportions of the estimated population (40 and 33% respectively) were also found in the oceanic waters of Zone 5 (Fig. 3). Fewer dugongs were found in zones other than 4 and 5.

In all but two surveys (May and July), the highest dugong densities occurred in Zone 4 (Fig. 4). Dugong density estimates in Zone 4 ranged from 0.49 dugongs km^{-2} in winter (July) up to 2.34 dugongs km^{-2} during spring and summer. This represents densities over intertidal seagrass beds of up to 7.25 dugongs km^{-2}. In contrast, dugong densities in Zone 5 were highest in winter, 1.64 ± 0.59 (s.e.) and 1.18 ± 0.08 (s.e.) dugongs km^{-2} in May and July respectively (Fig. 4). As in Zone 4, dugongs occurred in only a small proportion of Zone 5 so that actual observed densities were much greater than overall zone densities would suggest (Fig. 4). Densities of dugongs in zones other than Zones 4 and 5 were generally low. Beaufort Sea State was not a significant factor influencing estimation of dugong density ($F = 0.76$, $P = 0.38$).

Group size and composition

Between 45% (May) and 85% (December) of dugongs in Moreton Bay were found in herds (groups >10 dugongs) on any one survey (Fig. 3). Dugongs were more likely to be associated in larger herds during the spring and summer months than during winter (Fig. 5). No large herds (>100 dugongs) were encountered in May and July. At these survey times, dugongs were more dispersed (Fig. 3) and were found

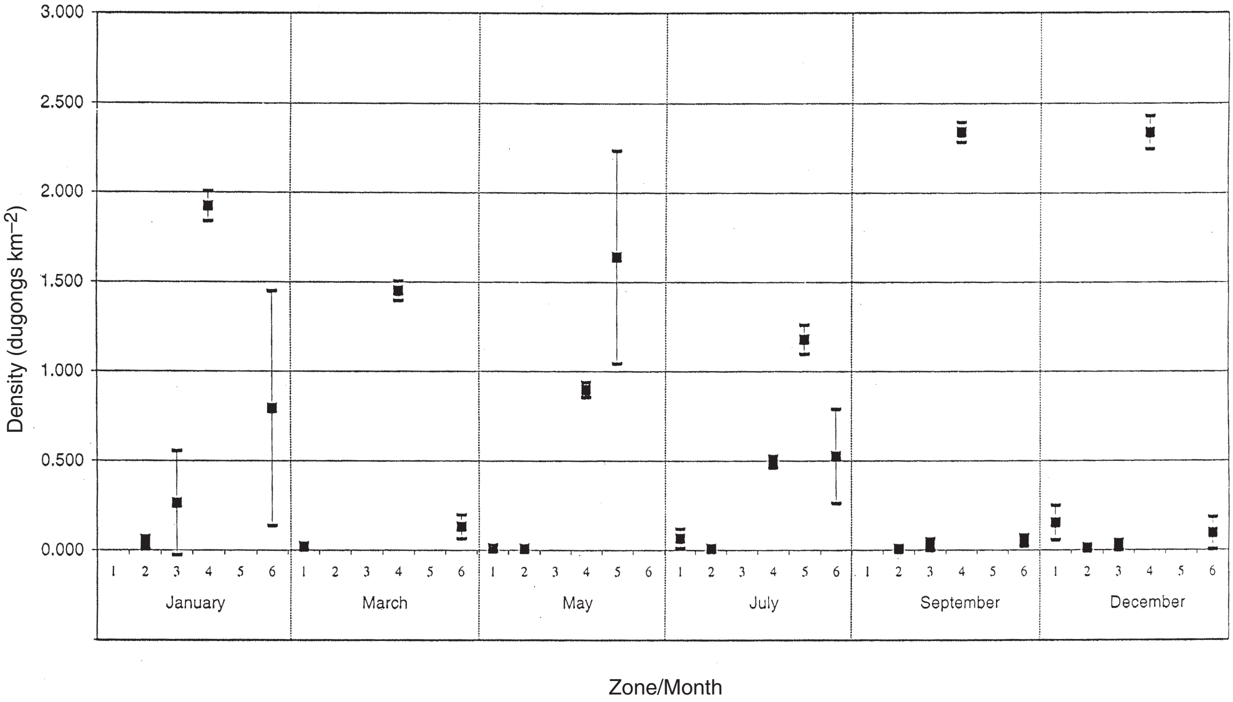

Fig. 4. Dugong density (mean ± s.e.) per zone per survey, Moreton Bay.

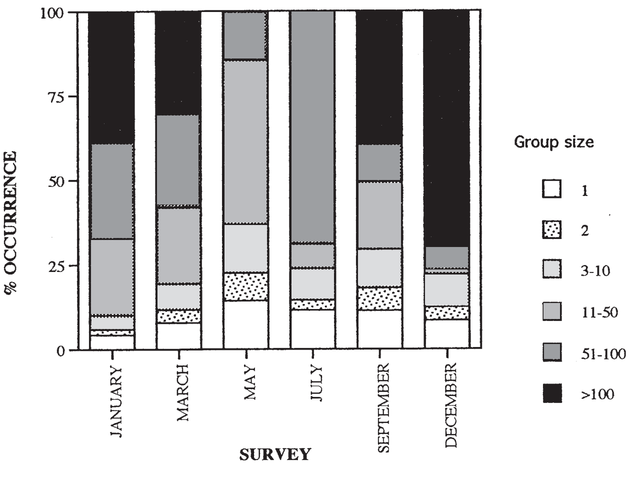

Fig. 5. Percentage occurrence of dugong groups in each group size category for each of the six aerial surveys.

in smaller aggregations (Fig. 5). Mean group size was greatest in January (14.4 ± 6.22) and smallest in May (4.2 ± 0.96). The largest herd (approximately 300 dugongs) was encountered in September.

The percentage of calves in the population varied from 1.31% (September) to 7.04% (May) (Table 2). The low calf count in September is likely to be an underestimate since no calf count was obtained from the largest herd of 300 dugongs, due to turbid water conditions from intense dugong feeding activities. Excluding this underestimate, calves comprised a mean of 4% (±0.81) of the dugong population. Neonate calves were sighted in January, September and December.

Dugong distribution

Dugongs were dispersed over a large area of intertidal sandbanks in Zone 4 with particular hot spots regularly containing large herds. The most frequently inhabited areas at high tide included parts of the western Amity Banks, northern Moreton Banks and Rous Channel, a combined area of approximately 13 km^2 (Fig. 2). Dugongs were also frequently seen over the southern Moreton Banks, and were seen in the waters of South Passage and the Pacific Ocean (up to 7 km offshore from Moreton Island) in winter. Dugongs were occasionally seen over Warragamba Bank, mid-Moreton Banks and Chain Banks (Fig. 2) but were rarely encountered over southern Amity Banks, Wanga Wallen Bank and in Rainbow Channel.

Dugongs were also found infrequently in other parts of Moreton Bay (Fig. 3). Small numbers of dugongs were sometimes encountered in the southern bay and at Deception Bay, west of St Helena and Green Islands, in Redland Bay and offshore from Tangalooma Resort, Moreton Island. Three solitary dugongs were regularly seen at the same locations: off Wellington Point, off Manly Boat Harbour and in southern Pumicestone Passage. The dugong at Manly Boat Harbour was heavily scarred and appeared to be the one individual.

Comparison with 'Preen' survey design

239 dugongs were seen on the survey conducted using the design of Preen (1993) (Fig. 2) whereas 630 were seen over the same area on the same day using the present survey design.

Discussion

Population size estimates

The results of the present surveys suggest that a population of some 850–1000 dugongs lives in Moreton Bay. The uncorrected count of 857 dugongs sighted on non-overlapping transects in December represents the minimum population estimate. These surveys confirm Preen's (1993) findings that Moreton Bay supports a significant dugong population.

The high degree of temporal variation in population estimates suggests that pooling of surveys to obtain an estimate of mean population size is meaningless. Population estimates were higher and less variable in the spring–summer months of January, September and December than in March, May and July. As Preen's (1993) studies indicate that dugongs are probably resident within Moreton Bay year-round, these diverse population estimates probably result from temporal variation in sightability. The lower winter counts may be due to a decline in number of herds and mean herd size as dugongs disperse across the eastern banks region and out through South Passage into warmer oceanic waters, and do not necessarily mean that there were fewer dugongs in Moreton Bay and its environs during winter. These movements are likely to affect sightability of dugongs and hence population size estimates as (i) small groups are less visible to aerial observers than larger herds, and (ii) dugongs are less easily sighted in the deeper waters of Rous Channel and the Pacific Ocean. In fact, different correction factors may be required when dugongs are in deeper water, as dugongs probably become less visible with increasing water depth, and may alter their dive patterns (Lanyon and Sneath, unpublished).

Preen (1993) also found high inter-survey variability in estimates of the Moreton Bay dugong population (range: 210–569) but no evidence of a seasonal trend in these estimates nor in propensity of dugongs to herd. Preen's surveys may have missed large dugong herds, restricting his ability to detect temporal patterns. The present surveys show that Preen's flight path missed areas of the banks that were consistently used by large numbers of dugongs in 1995.

Long-term changes in population size

The dugong population estimates reported here are the largest yet recorded for Moreton Bay. Uncorrected counts of dugongs in Moreton Bay have ranged from less than 300 in 1976 (Lear 1977) up to 850 in December 1995 (Table 4). However, this apparent upward trend in population size probably reflects changing survey techniques rather than an actual population increase due to immigration or recruitment.

It is likely that previous surveys underestimated the dugong population resident within the bay through irregular and/or unrepresentative survey designs. Unlike the present surveys, the principal aim of earlier surveys was to document distribution, rather than to estimate absolute abundance of dugongs (e.g. Preen 1993). In addition, it is possible that dugong distribution has altered in the bay. There is some evidence to suggest that, historically, large numbers of dugongs were found in the western and southern parts of the Bay (Welsby 1931; Peterken 1994) as well as over the Eastern Banks. Although this major shift in distribution is thought to have occurred by early this century (Peterken 1994), it is conceivable that at times over the past 20 years of surveys, some dugongs have been in areas other than the eastern bay and therefore were missed by surveys that principally surveyed this region. Similarly, perimeter surveys of Moreton Bay (e.g. Heinsohn and Marsh 1980) would presumably have missed dugongs in more central regions.

The clumped distribution of dugongs in Moreton Bay suggests that anything less than a systematic spatially intensive survey regime would tend to underestimate the population. For example, the irregular Preen survey design had the potential to miss large herds that may have been situated between transects. In addition, time of year at which the survey is conducted may also affect the estimation of population size if season is a critical factor. For example, the survey of Marsh *et al.* (1990) was one of the more spatially intensive survey designs but was conducted in June when an underestimate of the population might be expected. Accordingly, the population size estimated by Marsh *et al.* (1990) fell outside the range of estimates that I obtained (Table 4). It is probable that the change in survey design has had a major effect on population estimation.

It is also possible that the higher counts in the present surveys may be due to a real increase in the Moreton Bay population. From the mid-nineteeth century until the 1940s, a dugong oil industry operated in Moreton Bay (Peterken 1994). This fishery may have led to a depletion of the Moreton Bay dugong population. The apparent increase in the dugong population may represent a post-fishery population recovery through natural reproduction. On the basis of life-history parameters, Marsh (1988) calculated that the natural maximum population increase is only 5% per annum in dugongs. Thus the count of at least 300 dugongs in 1976 could have grown to about 800 by 1995, assuming that this initial population estimate was reliable. However, whether the Moreton Bay population could have sustained a mean increase of more than 5% per annum is problematic given the low observed calf counts.

The reproductive rate of dugongs in Moreton Bay has not been measured directly; however, a comparison of calf counts between surveys may indicate potential trends. In

Table 4. Summary of aerial surveys of Moreton Bay from 1977 to the present surveys
Total dugongs = uncorrected counts. % calves = percentage of the population represented by calves

Flight path / survey area	Date	Total dugongs (uncorrected)	% in Eastern Banks region + South Passage	% calves	Reference
24 transects traversed all bay between Peel and Bribie Islands	May 1977	210	95	6.7	Heinsohn (1977)
Western edge of Moreton and North Stradbroke Islands; some transects over eastern banks; South Passage region	May 1976	283	97.8	?	Lear (1977)
	September 1976	184	98.4	?	
	October 1976	148	98.6	?	
	December 1976	118	100.0	?	
	January 1977	268	99.1	?	
Perimeter survey of Moreton Bay; some transects over eastern banks	August 1979	307	82	5.5	Heinsohn and Marsh (1980)
Strip transect survey of entire bay; South Passage region	June 1985	168	98.8	7.7	Marsh *et al*. (1990)
'Standard' strip-transect survey of eastern banks × 28 times (includes 2 perimeter surveys of bay)	July 1988 – February 1990	201–569	94.6 (summer) 98.8 (winter)	7.1–15.9 (mean 10.1)	Preen (1993)
'Standard' strip-transect survey of eastern banks + perimeter survey (Heinsohn 1979)	April 1993	664	96.4	?	Preen and Marsh (1995)
Strip-transect survey of entire bay; South Passage region	January 1995 – December 1995	347–857	88.7–98.2%	2.5–7.04	This study

these surveys, calves comprised 2.5–7% of the observed population, compared with 5.5–10.1% for earlier Moreton Bay surveys (Table 4), and 1.4–20.4% elsewhere in the dugong's range (Marsh *et al.* 1994). If calf counts are good approximations to reproductive rate in shallow clear-water environments such as Moreton Bay (i.e. where calves are highly visible), and if dugongs of up to two years of age are counted as calves on aerial surveys (Marsh *et al.* 1984), then the number of calves born per year in Moreton Bay is about half the number observed. This sets the estimated annual recruitment rate through calving to 2.75–5% for Moreton Bay, or a mean of only 2% for the current survey year.

The degree to which each of these factors has contributed to apparent increases in dugong counts cannot be quantified. Thus, Preen and Marsh's (1995) suggestion that the Moreton Bay population increased by about 100 animals over the three year period 1990–93 through immigration by dugongs from Hervey Bay must be viewed with caution. If the growth in the dugong population in Moreton Bay is real, then this is possibly the only area on the east coast of Australia that has shown a recent population increase. Dugong populations elsewhere in southern Queensland have shown a decline of more than 50% over the past decade (Marsh *et al.* 1996).

Habitat utilisation

Dugongs in Moreton Bay are most frequently seen above seagrass beds. These surveys confirm Preen's (1993) findings that the eastern Amity and Moreton Banks and the deep-water areas adjacent to these sandbanks comprise the most critical area for dugongs in Moreton Bay. These favoured areas are characterised by seagrass communities dominated by sparse *Halophila* spp. (*H. ovalis*, *H. spinulosa* and *H. decipiens*) with lesser amounts of *Halodule uninervis* (Preen 1993; Lanyon, unpublished). Low-biomass stands of these seagrasses (particularly *Halophila* species) constitute the preferred food of the highly selective dugong, both here and in other parts of its range (Marsh *et al.* 1982; Lanyon 1991; Preen 1993). The areas favoured by dugongs at high tide comprise the most extensive beds of these seagrasses on the eastern banks, and within Moreton Bay. The largest dugong herds in these areas occurred during spring and summer, coinciding with the growth periods of these seagrass species (Preen 1993; Lanyon and Marsh 1995).

Although a large proportion of the eastern banks region is used by dugongs at some time, one of the most striking features of the pattern of dugong distribution in the eastern banks region (and indeed elsewhere in the bay) is its very localised nature. The major concentrations and the largest aggregations of dugongs were repeatedly found over the same seagrass beds at high tide. These dugong 'hot spots' on the western Maroom and northern Coonungai Banks make up a relatively small proportion of the total eastern banks region (13 km^2 of a total seagrass area of approximately 110.5 km^2). The repeated regrazing of particular areas on the eastern banks has been described as a form of 'cultivation grazing' that serves to maintain the nutritional quality of the dugong's seagrass diet (Preen 1995).

In addition, the waters through Rous Channel and east of South Passage (up to 10 km offshore from Moreton Island) are frequently used in the cooler months (Preen 1993). These oceanic waters may provide warm-water refugia when water temperatures in Moreton Bay drop to about 18–19°C (Preen 1993; Steele and Kuhl 1993). Apart from the eastern banks seagrass area, only patchy dugong habitat remains in Moreton Bay. Relatively small seagrass areas in the southern bay are used by considerable numbers of dugongs year-round and dugongs may move between these areas and the eastern banks. The high concentrations of dugongs in parts of the eastern banks of Moreton Bay probably reflects the limited availability of suitable seagrass habitat. Local dugong densities of up to 7.25 km^{-2} are high compared with elsewhere in Australian waters (see Marsh *et al.* 1994). Densities as high as 1.25 dugongs km^{-2} were recorded in Hervey Bay in 1988 (Preen and Marsh 1995), and up to 5.1 dugongs km^{-2} in Shark Bay in 1989 (Preen *et al.* 1997). Whether these dense aggregations of dugongs at high tide in Moreton Bay are enforced feeding assemblages or herds with an underlying sociality is currently unknown. The repeated regrazing of seagrasses by dugongs in Moreton Bay may not be a foraging strategy, as suggested by Preen (1995), but merely the result of large numbers of animals in a limited space.

Management considerations

Whether the Moreton Bay dugong population is stable or increasing, there is certainly no evidence of the major declines that are occurring elsewhere on the Queensland coast (Marsh *et al.* 1996). The population declines further north have been mainly attributed to mortality caused by accidental drowning in commercial fishing and shark nets, to hunting by indigenous people, and to loss of coastal habitat (Marsh *et al.* 1996). Threats to Moreton Bay dugongs are probably different to elsewhere and may reflect the human activities in the bay and the dugongs' locations relative to human habitation. Major threats probably include mortality caused by boat strike, hunting by indigenous people, and also loss of coastal habitat, though the relative importance of these threats cannot be ascertained.

In the United States, management actions related to human-caused mortality of marine mammals depend on detecting a mortality rate that will lead to a decline rather then detecting declines in abundance (Wade 1998). The US Marine Mammal Protection Act now stipulates that this approach be taken so that mortality does not exceed a level that the population can sustain. This mortality level (or Potential Biological Removal, PBR) can be calculated from demographic data as

$$\mathrm{PBR} = N_{\mathrm{min}} \times 0.5R_{\mathrm{max}} \times F_{\mathrm{R}}$$

where N_{min} is the minimum estimate of animals in a stock and incorporates precision and variability associated with that estimate, R_{max} is the maximum rate of increase of the population and F_R is the recovery factor (Barlow *et al.* 1995). N_{min} is calculated as

$$N / \exp(z(\ln(1+ CV(N)^2))^{0.5})$$

where N = an abundance estimate, CV(N) = coefficient of variation, z = a constant factor 0.842.

PBRs based on the minimum and maximum spring–summer population estimates of 946 ± 23 and 1019 ± 166 respectively (giving N_{min} of 927 and 889 dugongs respectively), an R_{max} of 2% (based on estimated recruitment rate for the current year) and a maximum recovery factor (R_F) of 1, are close: 9.27 and 8.89 respectively, or only 9 dugongs per annum. However, R_{max} based on 2% recruitment rate in the current survey year may be low, given that the reproductive rates in dugong populations are variable between years (Marsh *et al.* 1984). Demographic data specific to Moreton Bay are unavailable at this stage; however, based on a 4% reproductive rate, which may be representative of more tropical populations (Marsh, personal communication), PBRs may be as high as 18 dugongs per annum. In either case, a PBR of between 9 and 18 dugongs represents a low mortality level.

As the Moreton Bay dugong population may sustain a maximum added mortality of only 1–2%, a very slight increase in natural mortality could lead to a population decline. The human population of the city of Brisbane is growing by 2.29% (or 35 000 people) per annum (Australian Bureau of Statistics 1998). Since increased human pressure through boating activities, commercial fish-netting, sediment run-off, eco-tourism, and hunting is likely to occur as the human population of the Moreton Bay catchment continues to increase, there is a very real threat of increasing dugong mortality. There is also a risk that damage to seagrass habitat will lead to a decline in dugong fecundity as dugong reproduction is likely to be nutritionally limited (Lanyon 1991). The Moreton Bay dugongs are found at the southern extreme of the species' range and are subject to thermal and nutritional stresses in winter (Preen 1993). This population is probably living close to its physiological limit and, as such, may be especially vulnerable to deleterious impacts.

A 50% decline in dugong numbers has occurred in the southern Great Barrier Reef region (Cooktown to Gladstone) in the past decade (Marsh *et al.* 1996). The Hervey Bay dugong population also declined by 50% in 1992, probably due to seagrass die-off caused by high sediment run-off during a flood, as a result of agricultural activities in that bay's catchment (Preen and Marsh 1995). The related manatee of Florida in the Unites States has also suffered high mortality associated with increased urbanisation and usage of coastal waterways (Ackerman *et al.* 1995). Similar population declines could presumably occur in Moreton Bay, particularly with increasing human population. The present study provides an accurate population estimate for Moreton Bay dugongs so that any potential population decline could be detected through an appropriate monitoring programme.

Survey methodology

The Moreton Bay dugong population presents a unique set of conditions to the aerial surveyor. The population is large, concentrated over a small area, highly clumped and temporally variable with respect to distribution and sightability. The methodology used in these surveys has been developed to meet specific conditions. Doubling the altitude allows more time for observers to count large groups of dugongs without compromising sightability (Marsh and Sinclair 1989*a*) whilst maximising survey coverage. A census count of the principal dugong area mitigates the possibility of missing significant herds of dugongs lying between strip transects. I also recommend that all future surveys of Moreton Bay be conducted under constant favourable weather conditions, that the surveys be timed to exactly straddle the high-tide period, and that observers experienced in counting high densities of dugongs be employed. Further, temporal variation in counts suggests that surveys to estimate absolute abundance should be conducted at a consistent time of year, during the summer months. Since these aerial surveys, a mark–recapture study has commenced to validate these survey data and to collect demographic data specific to the Moreton Bay dugong population (Lanyon *et al.* 2002).

Acknowledgments

These surveys were funded by the Queensland Department of Environment (Surveys 2–6) and the Great Barrier Reef Marine Park Authority (Survey 1). Many thanks to Margaret Morrice for assistance in transcribing and editing survey tapes, and to Adnan Moussalli and Ms Morrice for assistance with data analysis. Ms Morrice's salary was funded by a University of Queensland New Staff Grant, and Mr Moussalli's by the Winifred V Scott Foundation. Many thanks to the observers (Sascha Brand, Nancy Fitzsimmons, Donna Groves, Dominique Harris, Anita Heidemann, John Kirkwood, Pia Laegsdgaard, Claire Peterken and Rob Slade) and also to the pilots (Helene Young and Dana Bradberry of Arena Aviation). The Partenavia aircraft was chartered from Sabair Toowoomba. Thanks also to Helene Marsh for loan of survey equipment, Ivan Lawler and Nina Morrissette for assistance with Fortran programs, Stephen Kelly for help with ArcView®, and Tony Preen for early discussions. Gordon Smyth, Joan Hendrikz and Gerry Quinn advised on the statistics. John Kirkwood and Helene Marsh critically reviewed this manuscript, and Lynn Pryor kindly assisted in preparation of the maps.

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Manuscript received 23 October 1998; accepted 30 January 2003