CSIRO PUBLISHING

Wildlife Research

Volume 24, 1997

A journal for the publication of original scientific research
in the biology and management of wild native or feral introduced vertebrates

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the Australian Academy of Science

Academy of Science

Wildlife Research, 1997, **24**, 185–208

Distribution and Abundance of Dugongs, Turtles, Dolphins and other Megafauna in Shark Bay, Ningaloo Reef and Exmouth Gulf, Western Australia

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Abstract

Strip-transect aerial surveys of Shark Bay, Ningaloo Reef and Exmouth Gulf were conducted during the winters of 1989 and 1994. These surveys were designed primarily to estimate the abundance and distribution of dugongs, although they also allowed sea turtles and dolphins, and, to a lesser extent, whales, manta rays and whale sharks to be surveyed. Shark Bay contains a large population of dugongs that is of international significance. Estimates of approximately 10000 dugongs resulted from both surveys. The density of dugongs is the highest recorded in Australia and the Middle East, where these surveys have been conducted. Exmouth Gulf and Ningaloo Reef are also important dugong habitats, each supporting in the order of 1000 dugongs. The estimated number of turtles in Shark Bay is comparable to the number in Exmouth Gulf plus Ningaloo Reef (7000–9000). The density of turtles in Ningaloo Reef and, to a lesser extent, Exmouth Gulf is exceptionally high compared with most other areas that have been surveyed by the same technique. Shark Bay supports a substantial population of bottlenose dolphins (2000–3000 minimum estimate). Exmouth Gulf and Ningaloo Reef were not significant habitats for dolphins during the winter surveys. Substantial numbers of whales (primarily humpbacks) and manta rays occur in northern and western Shark Bay in winter. Ningaloo Reef is an important area for whale sharks and manta rays in autumn and winter.

The Shark Bay Marine Park excludes much of the winter habitats of the large vertebrate fauna of Shark Bay. In 1989 and 1994, more than half of all the dugongs were seen outside the Marine Park (57·4 and 50·7%, respectively). Approximately one-third to one-half of turtles and dolphins were seen outside the Marine Park (in 1989 and 1994 respectively: turtles, 43 and 27%; dolphins, 47 and 32%). Almost all the whales and most of the manta rays were seen outside the Marine Park. Expansion of the Shark Bay Marine Park, to bring it into alignment with the marine section of the Shark Bay World Heritage Area, would facilitate the appropriate management of these populations. This would also simplify the State–Commonwealth collaboration necessary to meet the obligations of World Heritage listing. The coastal waters of Western Australia north of the surveyed area (over 6000 km of coastline) are relatively poorly known and surveys of their marine megafauna are required for wise planning and management.

Introduction

Western Australia has an extensive coastline, extending 12500 km over 21° of latitude and 16° of longitude. Southern and western coastal waters are relatively well known (Wilson *et al.* 1979; Pearce and Walker 1991), but knowledge of the habitats and marine fauna decreases northwards from the populated south-west (Marine Parks and Reserves Selection Working Group 1994). The central western coast, between 22 and 27°S, includes a number of areas of high conservation status, including the Shark Bay World Heritage Area and Ningaloo Marine Park. Effective management of these areas requires sound knowledge of their environments, including their importance for threatened and high-profile species. Hence, the distribution and

10.1071/WR95078 1035-3712/97/020185$05.00

abundance of dugongs and other megafauna of this region was assessed by aerial survey during the winter of 1989. Megafauna, in this context, are large marine vertebrates that can be surveyed from the air.

The 1989 survey established Shark Bay as a site of particular significance for dugongs (Marsh *et al.* 1994). It also documented a distribution pattern that was at odds with expectations (Anderson 1982, 1986; Marsh *et al.* 1994). Given the management implications of these findings, and the need to determine whether the population was stable, increasing or decreasing, a second regional survey was conducted in 1994. Five years is the recommended interval between repeat surveys of dugongs to detect population trends (Marsh and Saalfeld 1989*a*). Such surveys have demonstrated population stability in some areas (northern Great Barrier Reef) and alarming declines in others (central and southern Great Barrier Reef; Marsh *et al.* 1996). Here we document and compare the distribution and abundance of dugongs, turtles and dolphins in Shark Bay, Ningaloo Reef and Exmouth Gulf during the winters of 1989 and 1994. We also provide information on the distribution of whales, manta rays and whale sharks. Data on dugongs from the 1989 survey of Shark Bay have been presented previously (Marsh *et al.* 1994).

Shark Bay supports a dugong population of international significance, a large turtle population, and is important for small and large cetaceans. While the Shark Bay World Heritage Area encompasses virtually all the important non-migration habitat for these species in this region, the Shark Bay Marine Park does not. This anomaly has the potential for confusion and conflict due to the different management regimes that may be expected by State and Federal agencies in the World Heritage Area outside the Marine Park.

Ningaloo Reef and Exmouth Gulf support important populations of turtles and are significant habitats for dugongs. Manta rays and whale sharks are relatively common off the Ningaloo Reef in winter. Ningaloo Reef is well protected in the Ningaloo Marine Park, but Exmouth Gulf, which sustains an important trawl fishery and is covered by petroleum exploration permits, currently has no special conservation status.

Methods

Study Areas

Shark Bay is a 13000-km^2 embayment complex on the central Western Australian coast (25°30′S, 113°30′E). It experiences a semi-arid to arid climate and precipitation (200–400 mm per year) is greatly exceeded by evaporation (2000–3000 mm per year). Consequently, enclosed parts of the bay, particularly Hamelin Pool, are hypersaline (>42‰). About half the bay is metahaline (38–42‰), while the remainder, primarily the western and northern areas, has oceanic salinities (35–40‰; Fig. 1) (Logan and Cebulski 1970).

Shark Bay has been inscribed on the World Heritage List in recognition of its outstanding universal natural values (Department of Arts, Sport, the Environment, Tourism and Territories 1990; Department of Environment, Sport and Territories 1995). Seagrass meadows cover more than 4000 km^2 and are reported to be the largest in the world (Walker 1989). These meadows are composed predominantly of the temperate species *Amphibolis antarctica*, although there is recent evidence of large deep-water meadows dominated by the tropical species *Halophila spinulosa* (Anderson 1994). The bay supports a population of approximately 10000 dugongs (*Dugong dugon*), making it a habitat of international significance for this species (Marsh *et al.* 1994). Nesting beaches at the northern tip of Dirk Hartog Island are used annually by as many as 800–1000 female loggerhead turtles (*Caretta caretta*), which may represent 70% of the Western Australian breeding population (Prince 1994*a*). Monkey Mia, on the eastern coast of the Peron Peninsula, is renowned for the contact between humans and some members of the local population of bottlenose dolphins (*Tursiops truncatus*) (Smolker *et al.* 1992). The World Heritage Area includes the entire bay complex, excluding nearshore waters around Carnarvon (Fig. 1). The southern and eastern areas of the bay are included in the Shark Bay Marine Park and the Hamelin Pool Marine Nature Reserve (Department of Conservation and Land Management 1994) (Fig. 1).

Ningaloo Reef (22°30′S, 113°48′E) is the largest fringing barrier reef in Australia and extends 260 km north–south along the western shore of the Cape Range Peninsula (Department of Conservation and Land Management 1989) (Fig. 1). It is mostly enclosed by Ningaloo Marine Park (Marine Parks and Reserves Selection Working Group 1994). Unlike most other coral reef systems in Australia, Ningaloo's near-shore reefs enclose a narrow lagoon varying in width from 200 m to 6 km and with an average depth of only 4 m

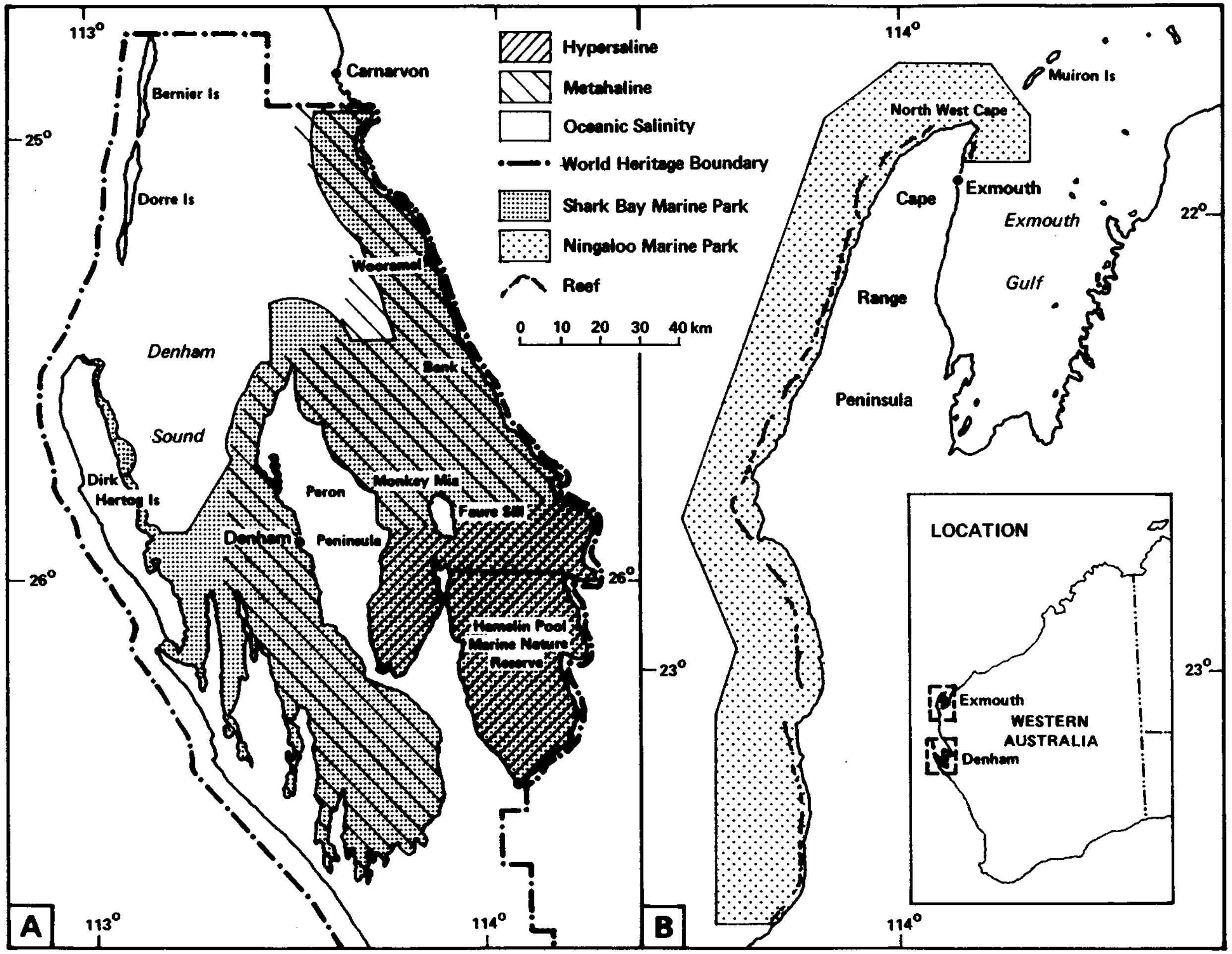

Fig. 1. Location of (*A*) Shark Bay and (*B*) Ningaloo Reef and Exmouth Gulf, showing the boundaries of the Shark Bay World Heritage Area, Shark Bay Marine Park and Ningaloo Marine Park. The salinity regime of Shark Bay is also indicated.

(Department of Conservation and Land Management 1989). Because of the aridity of the hinterland, and consequent low run-off, the lagoon waters are particularly clear (May *et al.* 1983), especially when compared with most inshore reef waters in Australia. Ningaloo Reef is contiguous to Exmouth Gulf (22°0′S, 114°24′E), which lies on the eastern side of the Cape Range Peninsula (Fig. 1). Exmouth Gulf is a relatively turbid environment, characterised by areas of fringing mangroves, mudflats, rock pavements and soft-bottom habitats. Early shoreline aerial surveys indicated that Exmouth Gulf was an important habitat for dugongs (Prince *et al.* 1981).

Aerial Surveys

We conducted strip-transect aerial surveys of Shark Bay, Ningaloo Reef and Exmouth Gulf between 4 and 13 July 1989 and between 21 and 30 June 1994. The surveys were conducted during winter to take advantage of the relatively light winds, and hence better observation conditions. The Shark Bay surveys encompassed the entire World Heritage Area, except for the western shorelines of the barrier islands (Fig. 2). The Exmouth surveys covered all of Exmouth Gulf, as defined by an east–west line through the tip of North West Cape (Fig. 2). The Ningaloo surveys encompassed only the near-shore waters of Ningaloo Marine Park (most of the park is deep and oceanic and was excluded). Unsuitable weather prevented the survey of the southern half of the Marine Park in 1989.

The methods followed those of Marsh and Sinclair (1989*a*, 1989*b*) and are detailed for the 1989 Shark Bay survey in Marsh *et al.* (1994). To calculate regional densities of fauna, Shark Bay was divided into eight survey blocks (Fig. 2). Ningaloo Reef and Exmouth Gulf were treated as single blocks, with a small

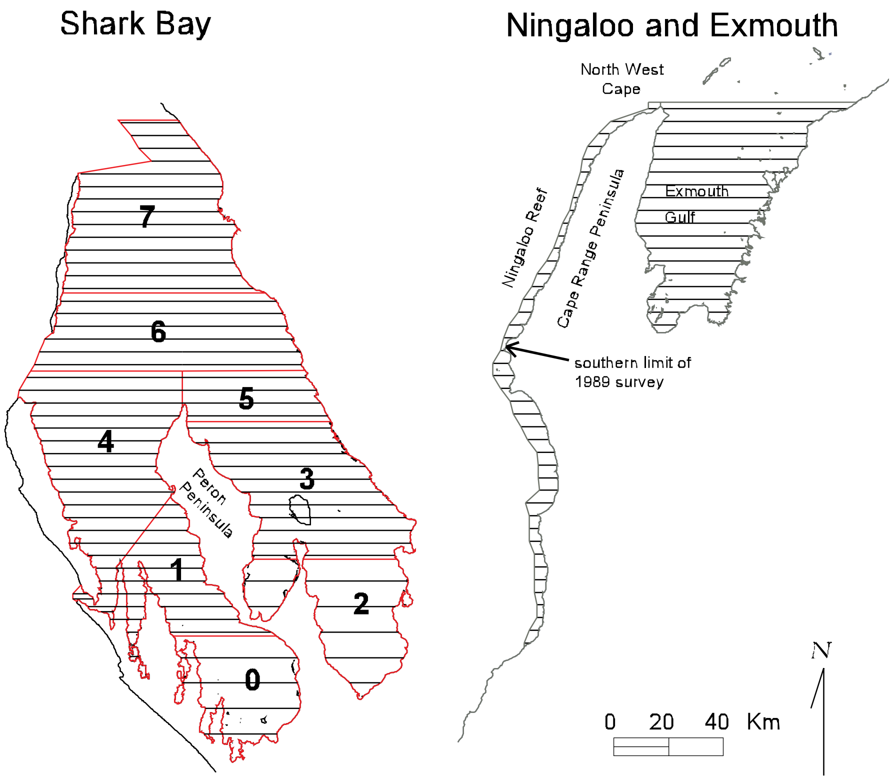

Fig. 2. Survey blocks (numbers) and flight transects (lines) used for the 1989 and 1994 aerial surveys of Shark Bay, Ningaloo Reef and Exmouth Gulf. Fewer transects were flown over Ningaloo Reef in 1989, but they were longer (not indicated).

part of Ningaloo Marine Park included in the Exmouth block (Figs 1, 2). The parallel east–west-oriented transects were 4·65 km apart (2·5′ latitude), resulting in a coverage of 8·9–9·9%, except in Shark Bay Blocks 0 and 2, where transects were 9·3 km apart, and coverage was 4·1%. The same transects were flown on each survey, except for Ningaloo Reef. In 1989, 19 transects, covering only the northern half of Ningaloo Marine Park, were surveyed (Fig. 2). In 1994, 43 transects (including the original 19), covering the full length of Ningaloo Marine Park, were flown. The 1994 transects extended approximately 200 m seaward of the fringing reef, while the 1989 transects extended 0·8–4·5 km (mean = 2·3 km) further.

Surveys were conducted only under good weather conditions (Beaufort sea state ⩽3; Table 1), and we avoided flying during periods of severe glare (early morning, late afternoon and midday). Sightings were recorded from a 200-m-wide strip on each side of the aircraft, from an altitude of 137 m, at an aircraft speed of about 185 km h^{-1}.

Table 1. Weather conditions encountered during aerial surveys of Shark Bay and Ningaloo Reef and Exmouth Gulf in 1989 and 1994

Values for wind speed, cloud cover and cloud height are the range of values recorded at the start of each flying session. Values for Beaufort sea state and glare are the mean of the modes for each transect, with range in parentheses. Glare is measured as follows: 0, none; 1, <25% of field of view affected; 2, 25–50% affected; 3, > 50% affected

Variable	Shark Bay		Ningaloo–Exmouth	
	1989	1994	1989	1994
Wind speed (km h^{-1})	0–37	0–28	0–10	0–33
Cloud cover (oktas)	0–8	0–6	0	0–1
Minimum cloud height (m)	750–3650	1000–8000	–	300
Beaufort sea state	1·66 (0–4)	0·99 (0–3)	1·54 (0–3)	1·37 (0·5–2·0)
Glare				
North	1·43 (0–3)	1·25 (0–3·0)	1·69 (0–3)	1·65 (0–3·0)
South	0·01 (0–3)	0·03 (0–0·5)	0	0·07 (0–1·0)

Two isolated, independent observers were used on each side of the aircraft. From a mark–recapture analysis of sightings, perception-bias correction factors were derived to adjust the results to allow for the animals visible, but missed by observers (Marsh and Saalfeld 1989*a*) (Table 2). Separate perception-bias correction factors were calculated for each side of the aircraft for dugongs and turtles for Shark Bay and for the combined Ningaloo–Exmouth blocks. Owing to the low number of dolphins recorded in Exmouth Gulf, the Shark Bay correction factor was used. Insufficient dolphins were seen in Ningaloo to derive population estimates, so no correction factors were needed.

Availability correction factors were derived to correct for the number of animals not at the surface, and hence less likely to be available to observers, at the time the plane passed over (Marsh and Sinclair 1989*b*) (Table 2). For dugongs, the proportion of sightings at the surface was compared to the proportion at the surface in Moreton Bay, Queensland, where all dugongs feeding in 2–3 m of water were visible. That proportion was determined from vertical aerial photographs. The availability correction factor makes the untested assumption that the proportion of dugongs at the surface is constant across depths, time and activities. Although this is improbable, this correction factor is likely to be conservative and provides a means of standardising for repeat surveys of the same area. The availability correction factors for turtles were calculated by standardising against the number of turtles seen at the surface in a survey of the northern Great Barrier Reef (Blocks 8–13; Marsh and Saalfeld 1989*b*). The proportion of turtles sighted at the surface on that survey was the lowest of any survey we have undertaken. The availability correction factor for turtles is likely to be a considerable underestimate because (i) the correction factor does not fully account for turtles not visible below the surface, (ii) small turtles are very difficult to see at the survey altitude, and (iii) turtle sightings are particularly dependent on sea surface conditions (Marsh and Sinclair 1989*a*).

Table 2. Group-size estimates and correction factors used to derive the population estimates for dugongs, turtles and dolphins in Shark Bay, Ningaloo Reef and Exmouth Gulf in the winters of 1989 and 1994

Area	Year	Group size (C.V.)	Perception correction factor (C.V.)		Availability correction factor (C.V.)
			Port	Starboard	
			Dugongs		
Shark Bay	1989	1·48 (0·03)	1·03 (0·01)	1·04 (0·01)	2·45 (0·12)
	1994	1·45 (0·06)	1·04 (0·01)	1·09 (0·02)	3·35 (0·12)
Exmouth	1989	1·48 (0·03)	1·03 (0·01)	1·04 (0·01)	2·45 (0·12)
	1994	1·48 (0·14)	1·11 (0·09)	1·19 (0·11)	3·90 (0·15)
Ningaloo	1989	1·48 (0·03)	1·03 (0·01)	1·04 (0·01)	2·45 (0·12)
	1994	1·48 (0·14)	1·11 (0·09)	1·19 (0·11)	3·90 (0·15)
			Turtles		
Shark Bay	1989	1·10 (0·02)	1·12 (0·01)	1·11 (0·01)	1·39 (0·08)
	1994	1·10 (0·03)	1·13 (0·02)	1·14 (0·04)	1·98 (0·09)
Exmouth	1989	1·10 (0·02)	1·12 (0·01)	1·11 (0·01)	1·39 (0·08)
	1994	1·11 (0·04)	1·67 (0·10)	1·62 (0·09)	1·59 (0·14)
Ningaloo	1989	1·10 (0·02)	1·12 (0·01)	1·11 (0·01)	1·39 (0·08)
	1994	1·12 (0·05)	1·67 (0·10)	1·62 (0·09)	1·93 (0·12)
			Dolphins		
Shark Bay	1989	2·57 (0·10)	1·05 (0·02)	1·04 (0·01)	1·00 (0·00)
	1994	2·00 (0·18)	1·06 (0·02)	1·14 (0·04)	1·00 (0·00)
Exmouth	1989	2·57 (0·10)	1·05 (0·02)	1·04 (0·01)	1·00 (0·00)
	1994	2·00 (0·18)	1·06 (0·02)	1·14 (0·04)	1·00 (0·00)

Availability correction factors were calculated separately from the proportion of dugongs sighted at the surface in Shark Bay and in Ningaloo–Exmouth (the proportion of dugongs at the surface did not vary significantly between Ningaloo and Exmouth: $\chi^2 = 0{\cdot}046$, d.f. = 1, $P = 0{\cdot}829$). Large numbers of turtle sightings allowed availability correction factors to be calculated separately for Shark Bay, Ningaloo and Exmouth. Availability bias was not corrected for dolphins because of the lack of suitable data to use as a standard.

The surveys were designed primarily to census dugongs. Within that constraint, it was normally not possible to circle to positively identify small cetaceans, so they have been analysed as a single group. Similarly, it is difficult to reliably separate green (*Chelonia mydas*), loggerhead and other turtles at the survey altitude, so they too have been grouped together.

As the transects were of variable length, the ratio method (Jolly 1969) was used to estimate the density, population size and associated standard errors for each block. The population estimates were based on the estimated number of animals of each group of fewer than 10 animals for each tandem team per transect, calculated with the appropriate corrections for perception and availability bias and mean group size. The standard errors were adjusted to incorporate the error associated with each correction factor (Table 2), as outlined by Marsh and Sinclair (1989*a*). Herds of 10 or more dugongs are excluded from the calculation of population estimates, and added to the population estimate as a separate stratum, as suggested by Norton-Griffiths (1978).

The significance of the differences between the abundance of dugongs, dolphins and turtles in Shark Bay in 1989 and 1994 was tested by ANOVA, both with and without the modal Beaufort sea state for each transect as the covariate. Blocks and times were treated as fixed factors and transect as a random factor nested within block. Input data for all analyses were corrected densities per square kilometre, with each transect contributing one density per survey, based on the combined corrected counts of both tandem observer teams. The densities were transformed [$\log_{10}(x + 1)$] to equalise the error variances. The differences between surveys of the Exmouth Gulf were examined by two-way ANOVA with transect as the blocking factor. The differences between surveys of Ningaloo Reef were not compared statistically because of the differences in the number and lengths of transects.

Sea-surface Temperatures

The best available satellite images of the sea-surface temperatures in the survey areas were obtained for 6 July 1989 (1520 hours, local time) and 23 June 1994 (0717 hours). Temperatures of the sea surface were derived from AVHRR Bands 4 and 5 by means of an algorithm by McMillin and Crosby (1984) and were correct to approximately 0·5°C. Only the top few millimetres of the sea surface is measured, so the recorded temperatures could be affected by the time of day that the images were acquired.

Results

Shark Bay

Dugongs

During the 1989 survey, 297 dugongs were seen in herds of less than 10. Two large herds (>40 and >100 dugongs) were also recorded. The mean group size (for herds <10) was 1·48 (± s.e. 0·04). The estimated population was 10 146 (± 1665), with an average population density of 0·71 (± 0.12) dugongs km^{-2} (Table 3). Calves made up 19% of dugongs sighted.

In the winter of 1994, we counted 290 dugongs on transects, of which 16·6% were calves. The mean group size was 1·45 (± 0·08; Table 2), and the largest group comprised only seven dugongs. A ‘herd’ of at least 200 dugongs was encountered just north-west of Denham, but the dugongs were dispersed over approximately 10 km^2, so this aggregation was not treated separately. The estimated population of 10 529 (± 1464), and the average density of 0·71 (± 0·10) km^{-2}, were very similar to the 1989 estimates (Table 3).

Comparing the two surveys, there was a significant year-by-block interaction, although inclusion of Beaufort sea state as a covariate suggests that this effect was marginal (Table 4). In 1989, most dugongs were seen in Blocks 4 and 5 (Fig. 3), and the greatest density (5·1 km^{-2}) was in Block 5 (Table 3). In 1994, most dugongs, and the greatest density of dugongs (2·8 km^{-2}), occurred in Block 4 (Fig. 3; Table 3).

In 1989, the distribution of dugongs appeared to be partly determined by water temperature, with less than 4% of dugongs seen in water colder than 18°C. This pattern was maintained in 1994, but not as strongly, as 13·8% of dugongs occurred in water colder than 18°C (Fig. 3).

Turtles

A total of 326 turtles was seen on transects in 1989, compared with 365 in 1994, most of which could confidently be identified as green turtles. The 1989 population estimate was 6373 (± 710) turtles at an average density of 0·43 km^{-2}. In 1994, the population estimate was 8431 (± 758), at an overall density of 0·57 km^{-2} (Table 3). Comparing surveys, there were significant effects of year and year-by-block, with or without the inclusion of Beaufort sea state as a covariate. This suggests that the different distribution of turtles between years is not accountable to a difference in observation conditions.

In 1989, most turtles were seen in the relatively deep water of Blocks 3, 5 and 6 (eastern side). In 1994, however, far fewer turtles were seen in these locations. Instead, most were seen in the shallow waters of the Wooramel Bank and Faure Sill, to the east and south of this area (Figs 2, 4).

The 1989 distribution of turtles tends to match the pattern in surface water temperature (Fig. 4), with 31·3% of turtles sighted in water colder than 18°C. In 1994, however, half (50·6%) of the turtles were seen in water colder than 18°C. It is unlikely that these differences are due to major changes in the bay’s thermal patterns between the time of image capture and aerial survey. The 1994 image was taken just two days before Blocks 6, 5 and 3 were flown, while in 1989 these blocks were surveyed 4–6 days after the image was captured.

Table 3. Block areas, survey intensity (cover) and population estimates of
Only the northern half of Ningaloo Reef was surveyed in 1989. Too few

Block	Area (km^2)	Cover (%)	Dugongs			
			Density (km^{-2})		No.	
			1989	1994	1989	1994
Shark Bay						
0	1198	4·24	0	0	0	0
1	1160	9·78	0	0·09 ± 0·06	0	106 ± 66
2	1631	4·05	0	0	0	0
3	2389	9·46	0·07 ± 0·03	0·30 ± 0·12	170 ± 68	710 ± 288
4	2726	9·93	1·69 ± 0·31	2·78 ± 0·51	4467 ± 819	7582 ± 1401
5	812	9·41	5·11 ± 1·50	0·74 ± 0·13	4040 ± 1171	599 ± 109
6	2243	9·82	0·60 ± 0·17	0·36 ± 0·08	1293 ± 847	798 ± 181
7	2747	9·90	0·07 ± 0·03	0·27 ± 0·08	176 ± 90	734 ± 222
Total	14906	8·69	0·71 ± 0·12	0·71 ± 0·10	10146 ± 1665	10529 ± 1464
Exmouth	3180	9·2	0·33 ± 0·10	0·32 ± 0·16	1062 ± 321	1006 ± 494
Ningaloo						
1989	555	8·3	1·14 ± 0·23		634 ± 127	
1994	869	8·9		1·11 ± 0·37		968 ± 320
Total						
1989	3735	9·1	0·45 ± 0·09		1696 ± 3453	
1994	4049	9·2		0·49 ± 0·40		1974 ± 588

Dolphins

In all, 212 dolphins in 85 groups were seen during the 1989 survey. The largest group comprised 15 animals. In 1994, 185 dolphins were sighted in 91 groups, with 10 the size of the largest group. Calves represented 8·1% of sightings in 1989 and 10·4% in 1994.

In 1989, 8% of dolphins were of unknown identity while 92% were identified as bottlenose dolphins; 75% of these identifications were described as 'certain'. In 1994, 80% of dolphins were identified as bottlenose (66% with certainty). Some 17% were unidentified, while three dolphins (1·6%) were believed to be *Stenella* species or *Delphinus delphis* and one (0·5%) was thought to be *Sousa chinensis*. Shark Bay may be beyond the normal southern limit for *S. chinensis* in Western Australia (Ross *et al*. 1994).

The estimated population of dolphins varied from 2888 (± 434) in 1989 to 2064 (± 267) in 1994 (Table 3). The overall density of dolphins was 0·19 km^{-2} in 1989 and 0·14 km^{-2} in 1994 (Table 3). No correction has been made for availability bias, so these are underestimates.

Comparing surveys, there were no significant effects or interactions (Table 4), reflecting the broadly similar distribution of sightings during each survey (Fig. 5). In 1994, there was a concentration of dolphins around the tip of Peron Peninsula (particularly Block 5) and an absence of sightings from Block 0. This lack of sightings is most probably due to the poor sighting conditions that developed during the 1994 survey of this block.

Other taxa

Fourteen whales were seen in 1994 (Fig. 6). The six that occurred within transects were humpbacks (*Megaptera novaeangliae*). In 1989, none of the seven whales sighted was within transects, although six were identified as humpbacks. Manta rays (*Manta birostris*) were frequently seen during the aerial surveys. These species occurred primarily in the deeper waters (>10 m) of oceanic salinity (Figs 1, 6). Population estimates have not been calculated for whales or manta rays. No whale sharks were seen in Shark Bay during either survey.

dugongs, turtles and dolphins in Shark Bay, Ningaloo Reef and Exmouth Gulf
dolphins were seen in Ningaloo Reef in 1994 to calculate population estimates

Turtles				Dolphins			
Density (km^{-2})		No.		Density (km^{-2})		No.	
1989	1994	1989	1994	1989	1994	1989	1994
0·20 ± 0·08	0·10 ± 0·11	242 ± 95	116 ± 134	0·27 ± 0·18	0	319 ± 216	0
0·45 ± 0·13	0·32 ± 0·08	523 ± 152	376 ± 89	0·26 ± 0·10	0·20 ± 0·04	296 ± 116	229 ± 42
0	0	0	0	0	0	0	0
0·46 ± 0·15	1·00 ± 0·23	1105 ± 351	2380 ± 559	0·25 ± 0·07	0·22 ± 0·06	593 ± 162	530 ± 146
0·64 ± 0·12	0·79 ± 0·12	1745 ± 339	2146 ± 324	0·26 ± 0·08	0·22 ± 0·07	700 ± 215	613 ± 192
1·04 ± 0·21	0·77 ± 0·21	848 ± 166	624 ± 167	0·24 ± 0·04	0·49 ± 0·09	198 ± 35	398 ± 7
0·64 ± 0·19	0·89 ± 0·10	1433 ± 437	1997 ± 223	0·26 ± 0·10	0·06 ± 0·02	587 ± 221	138 ± 34
0·17 ± 0·05	0·29 ± 0·09	477 ± 127	792 ± 233	0·07 ± 0·03	0·06 ± 0·03	195 ± 77	157 ± 72
0·43 ± 0·05	0·57 ± 0·05	6373 ± 710	8431 ± 758	0·19 ± 0·03	0·14 ± 0·02	2888 ± 434	2064 ± 267
1·42 ± 0·28	1·02 ± 0·22	4512 ± 877	3252 ± 684	0·16 ± 0·04	0·09 ± 0·03	496 ± 123	283 ± 93
4·51 ± 0·47		2503 ± 261		0·18 ± 0·06			
	4·90 ± 0·83		4260 ± 724			97 ± 30	
1·88 ± 0·25		7015 ± 915		0·16 ± 0·03			
	1·86 ± 0·25		7512 ± 996			593 ± 127	

Ningaloo Reef and Exmouth Gulf

Dugongs

In 1989, 57 dugongs were seen on transects in the Ningaloo and Exmouth blocks, compared with 40 in 1994, when an extra 24 transects were flown in the southern part of Ningaloo Marine Park. A very dispersed herd of about 50 dugongs was seen near North West Cape in 1989. This herd was excluded from the population model and later added to the population estimate. The population and density estimates for Exmouth Gulf changed very little between years: 1062 (± 321) dugongs at a density of 0·33 (± 0·10) km^{-2} in 1989 compared with 1006 (± 494) and 0·32 (± 0·16) km^{-2} in 1994 (Table 3). The difference between surveys was significant when Beaufort sea state was included as a covariate (Table 4). The significant transect effect indicates a different distribution pattern between years, but the marginally significant year effect also suggests a change in abundance (survey conditions were better in 1994, when fewer dugongs were seen). This could be due to dugongs moving across the arbitrary northern boundary of the Exmouth survey block.

Ningaloo Marine Park contained an estimated 968 (± 320) dugongs in 1994, while there were 634 (± 127) dugongs in the northern half of the Marine Park in 1989. The density of dugongs was very similar for each survey (1·14 ± 0·23 km^{-2} in 1989 and 1·11 ± 0·37 km^{-2} in 1994; Table 3). Because of the differences in survey design, the Ningaloo results have not been compared statistically.

The distributions of dugongs in Ningaloo Reef and Exmouth Gulf showed a broadly similar pattern between surveys, with most groups being sighted in the eastern half of Exmouth Gulf (Fig. 7). In 1989, 24% of dugongs were calves, compared with 20% in 1994. During both surveys, virtually all the waters in Ningaloo Reef and Exmouth Gulf were warmer than 18°C, and most were warmer than 20°C, and water temperature did not appear to account for the distribution of animals.

Table 4. Results of ANOVAs comparing the 1989 and 1994 densities of dugongs, turtles and dolphins in Shark Bay and Exmouth Gulf

Results are presented without covariates (1) and with Beaufort sea state as a covariate (2)

Source of variation	Dugongs						Turtles						Dolphins					
	d.f.		*F*		*P*		d.f.		*F*		*P*		d.f.		*F*		*P*	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Shark Bay																		
Transect nested in block[A]	59	59	2·00	2·04	0·004	0·004	74	74	2·35	2·73	0·000	0·000	71	71	1·77	1·71	0·009	0·013
Block[B]	4[C]	4[C]	17·74	21·98	0·000	0·000	6	6	3·77	3·50	0·002	0·004	5[D]	5[D]	1·95	2·34	0·097	0·050
Year[A]	1	1	0·55	0·57	0·461	0·453	1	1	7·55	0·16	0·008	0·694	1	1	1·86	0·36	0·177	0·552
Block by year[A]	4	4	3·06	2·50	0·023	0·052	6	6	2·40	2·77	0·036	0·018	5	5	1·21	1·22	0·315	0·309
Residual	59	58					74	73					71	70				
Regression[A]				3·33		0·073				14·61		0·000				0·27		0·603
Exmouth																		
Year	1	1	0·75	4·26	0·39	0·056	1	1	0·83	0·28	0·376	0·605						
Transect	17	17	1·70	2·61	0·141	0·031	17	17	1·36	0·82	0·265	0·652						
Residual	17	16					17	16										
Regression		1		6·51		0·21		1		0·32		0·58						

[A]Tested against residual.

[B]Tested against transect nested in block.

[C]Excludes Blocks 0 and 2, where no dugongs were seen.

[D]Excludes Block 2, where no dolphins were seen.

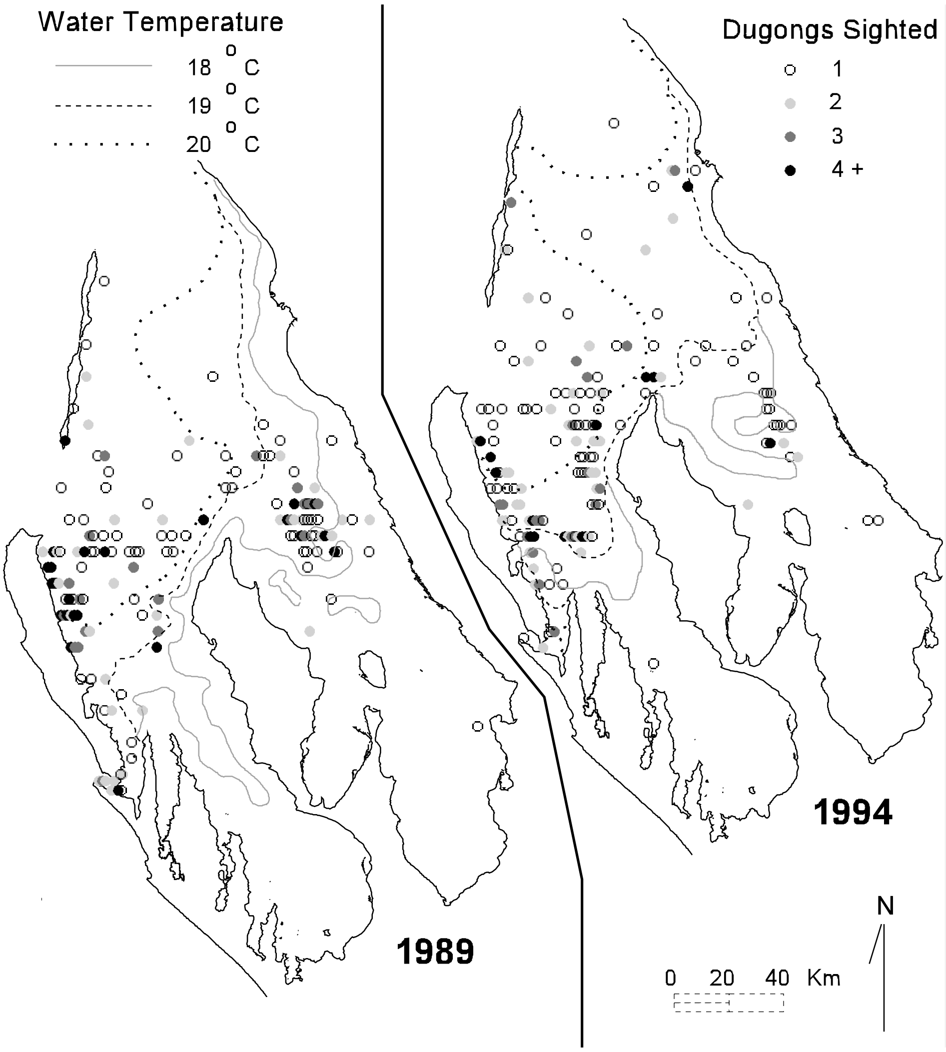

Fig. 3. Dugong sightings in Shark Bay in relation to water temperature in 1989 and 1994. Circles indicate the number of animals seen along 1 km of transect, and do not necessarily reflect group size.

Turtles

In 1989, 262 turtles were seen in Exmouth Gulf, compared with only 115 in 1994. The resulting population estimates were 4512 (± 877) in 1989 and 3252 (± 684) in 1994. The density of turtles was 1·4 (± 0·28) km^{-2} in 1989 compared with 1·0 (± 0·22) km^{-2} in 1994 (Table 3). These differences were not significant (Table 4). In 1989, 162 turtles were seen in northern Ningaloo Reef, which translates to a population estimate of 2503 (± 261) at a density of 4·51 (± 0·47) km^{-2}. In 1994, 119 turtles were seen over the full length of Ningaloo Marine Park, which represents a population estimate of 4260 (± 724) and a density of 4·90 (± 0·83) km^{-2} (Table 3). The distribution of turtles was broadly similar between years, although few turtles were seen in the deeper waters of central and western Exmouth Gulf in 1989 (Fig. 8).

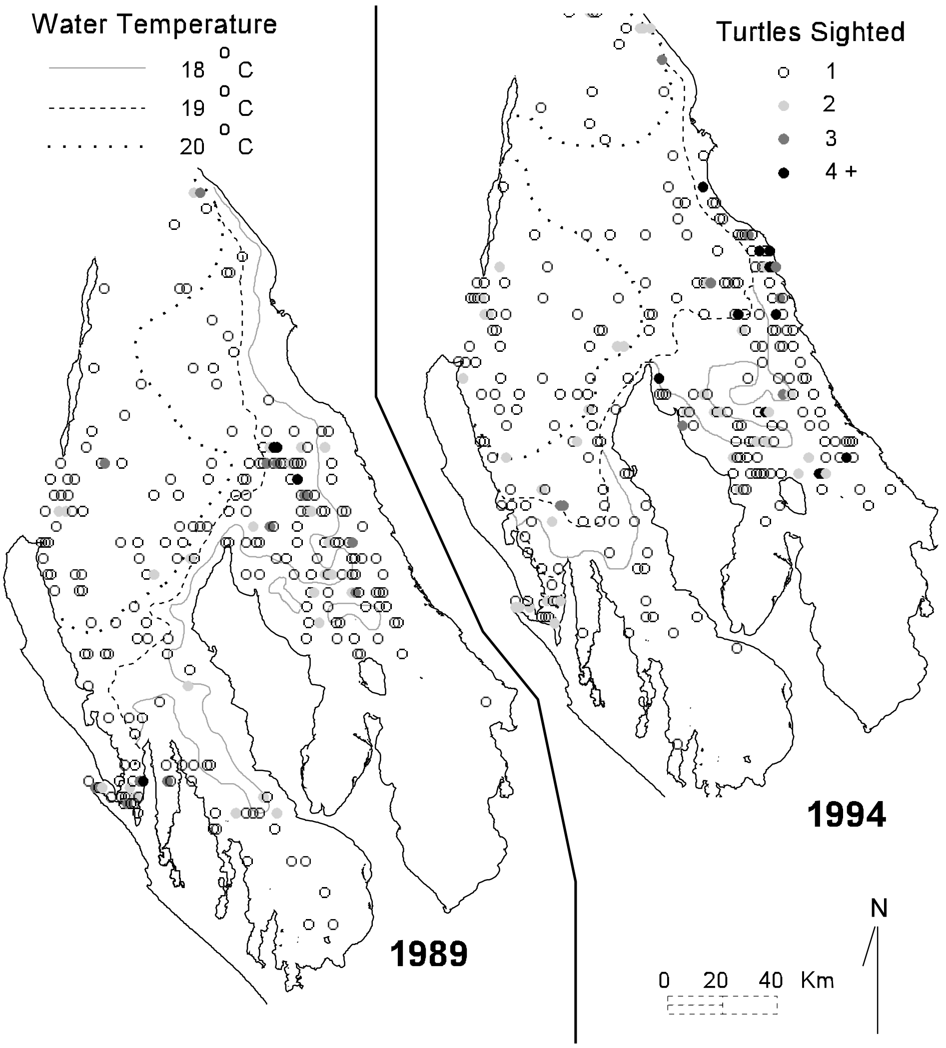

Fig. 4. Turtle sightings in Shark Bay in relation to water temperature in 1989 and 1994. Circles indicate the number of animals seen along 1 km of transect, and do not necessarily reflect group size.

Dolphins

In all, 59 dolphins were seen in 1989, compared with 24 in 1994. Bottlenose dolphins made up 76% of sightings in 1989 (82% called by observers as 'certain'), while 22% were unidentified, and one dolphin (1·7%) was identified as *S. chinensis*. In 1994, 33% of sightings were thought to be bottlenose (82% 'certain'), while 42% were unidentified and 25% were *S. chinensis*. The estimated populations and densities are shown in Table 3. The difference between surveys was not significant (Table 4). Very few dolphins were seen in Ningaloo on either survey (Fig. 9) and no population estimates have been calculated.

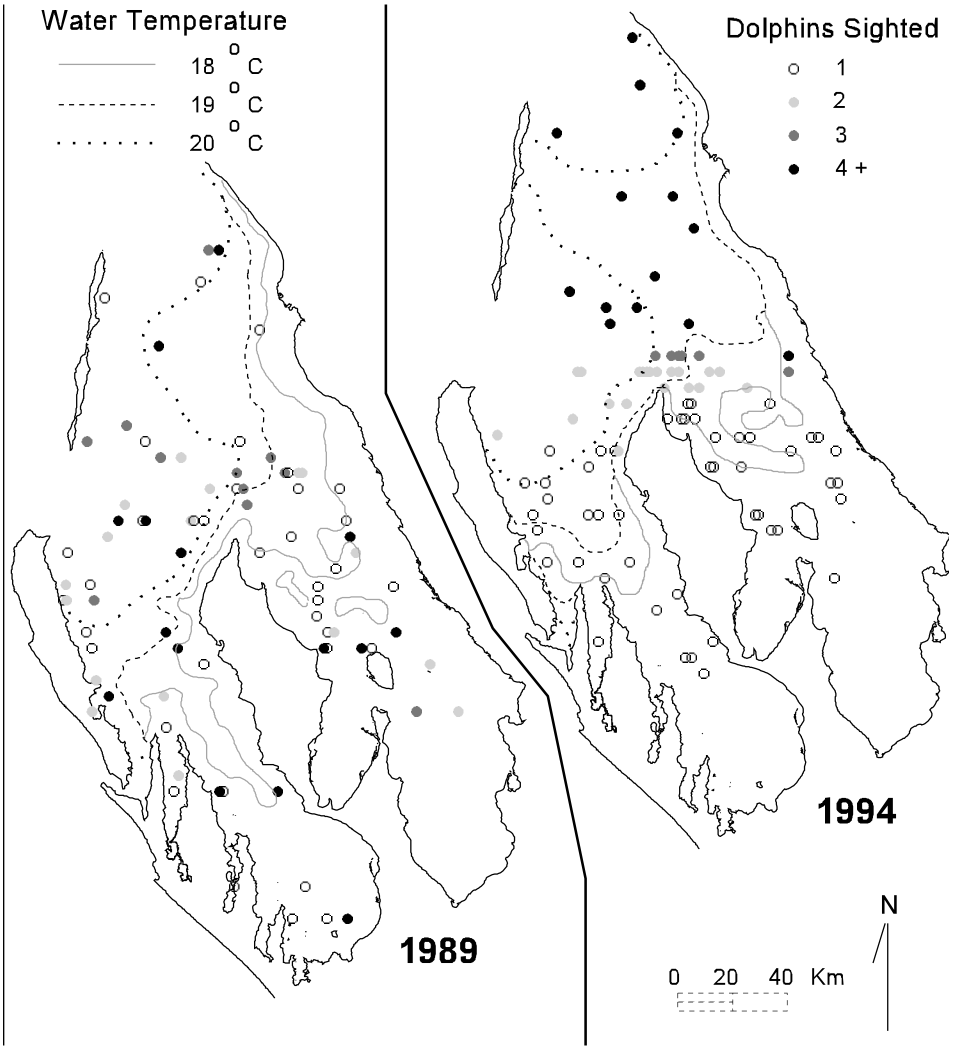

Fig. 5. Dolphin sightings in Shark Bay in relation to water temperature in 1989 and 1994. Circles indicate the number of animals seen along 1 km of transect, and do not necessarily reflect group size.

Other taxa

Manta rays were common in the northern half of Ningaloo Reef during both surveys (Fig. 10). In 1989, whale sharks (*Rhinodon typus*) were also common in the north of the Marine Park. No whale sharks were seen in 1994. A group of three humpback whales and a group of two unidentified whales were seen in the north of Ningaloo Marine Park in 1989 and 1994, respectively (Fig. 10).

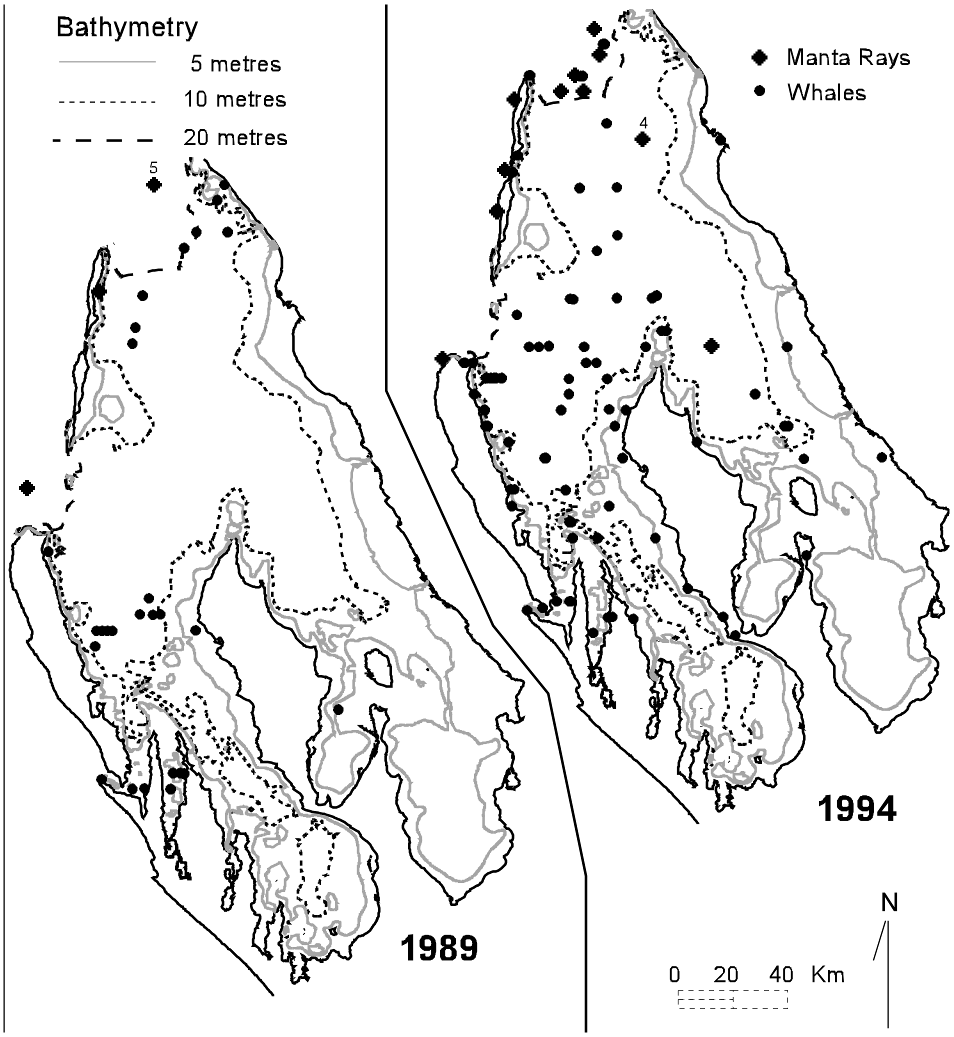

Fig. 6. Bathymetry of Shark Bay and the distribution of whale and manta ray sightings in 1989 and 1994. These maps include whales that were not on transects. Numbers indicate the size of groups (>1).

Discussion

Shark Bay

Dugongs

The consistency of results between the winter surveys of 1989 and 1994 confirms that Shark Bay supports a large population of dugongs, at a density (0·71 km^{-2}) that is notably higher than densities in other areas around Australia and the Middle East that have been surveyed by this method (see table 4 in Marsh *et al.* 1994). The only exception is Torres Strait, where two surveys returned density estimates of 0·44 ± 0·07 and 0·79 ± 0·11 dugongs km^{-2} in 1987 and 1991, respectively (Marsh *et al.* in press).

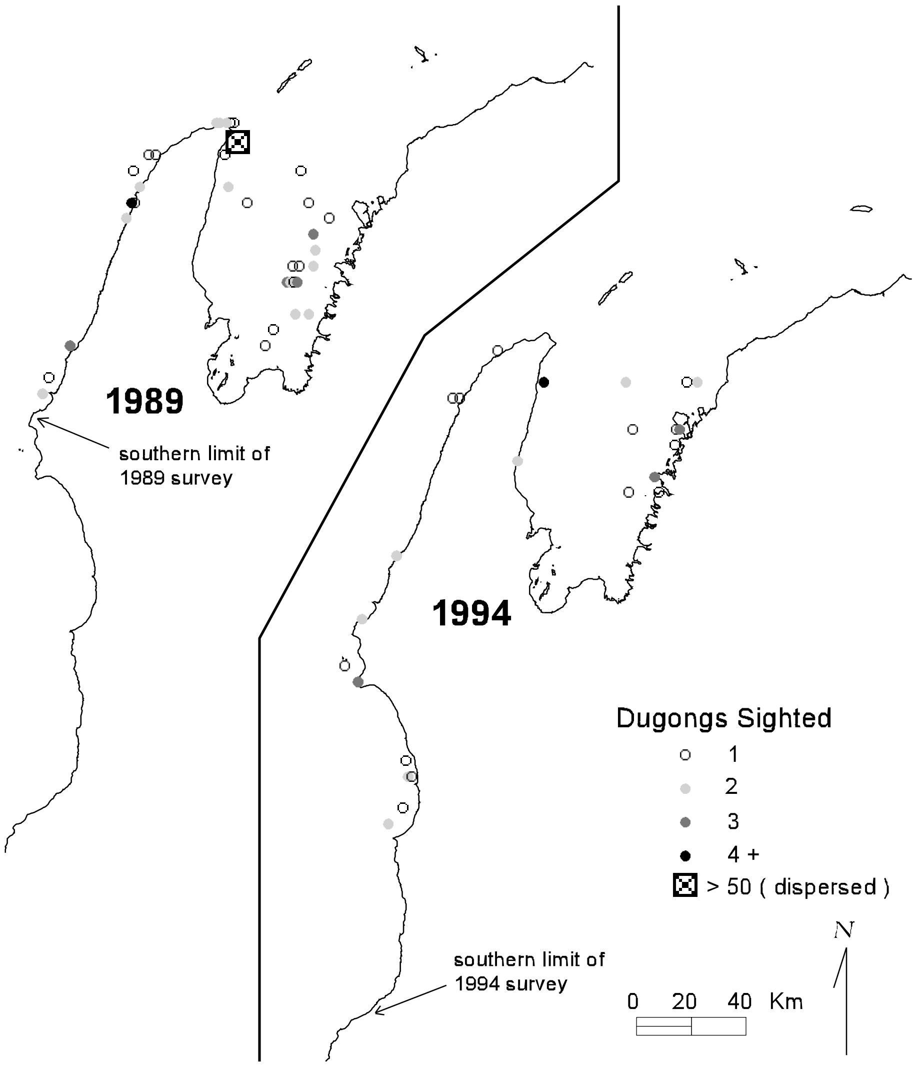

Fig. 7. Dugong sightings in Ningaloo Reef and Exmouth Gulf in 1989 and 1994. Circles indicate the number of animals seen along 1 km of transect, and do not necessarily reflect group size. The 1989 transects over Ningaloo Reef were longer than those of 1994.

The main difference between the results of the two surveys of Shark Bay was the change in dugong distribution. In 1989, dugongs were concentrated to the north-east of the Peron Peninsula, and along the eastern shore of northern Dirk Hartog Island (Fig. 3). In 1994, the dugongs were located primarily around the edge of Denham Sound: off the western side of northern Peron Peninsula and off the eastern shore of Dirk Hartog Island (Fig. 3). This difference may be of little significance, as the distance between the 1989 and 1994 areas of concentration (75–100 km) is well within the scale of movements regularly undertaken by dugongs (Marsh and Rathbun 1990; Preen, unpublished data). However, in late 1995 the seagrass in the vicinity of the 1989 concentration of dugongs in the east of the bay had disappeared (P. K. Anderson, personal

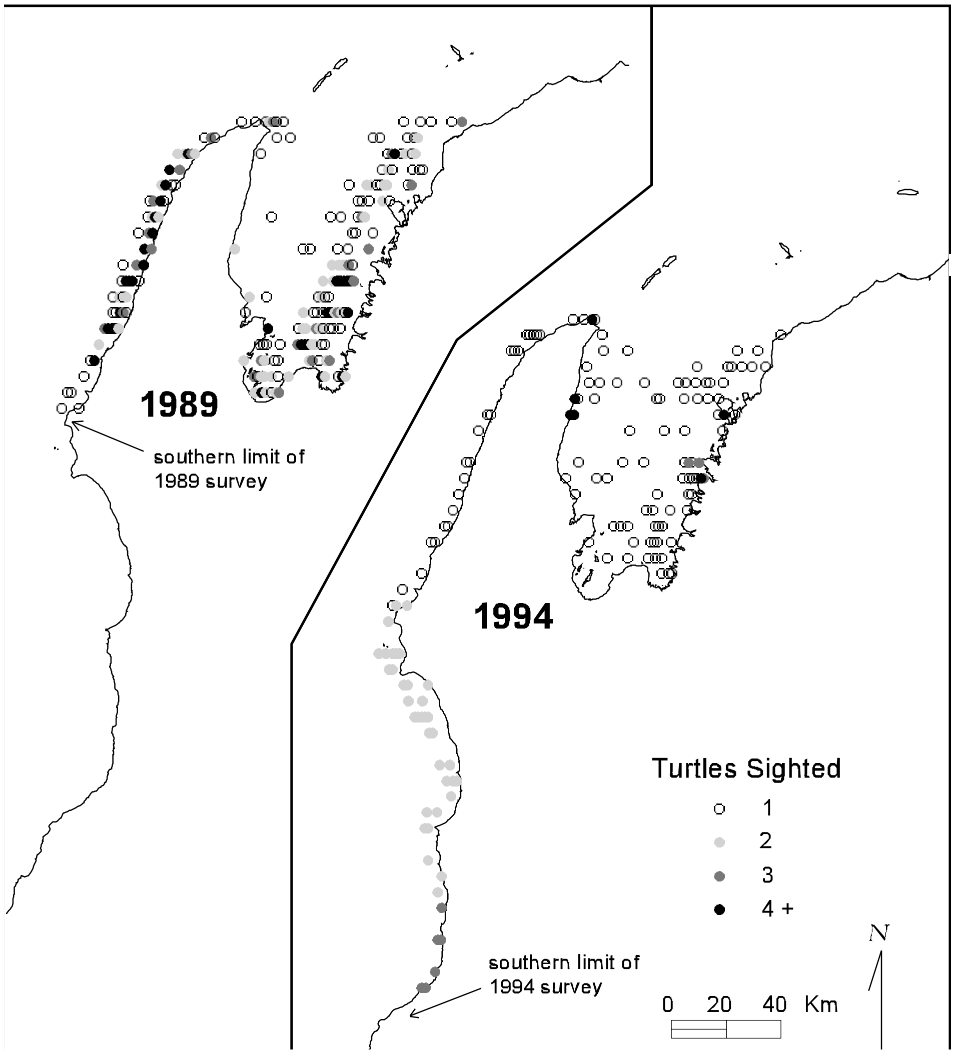

Fig. 8. Turtle sightings in Ningaloo Reef and Exmouth Gulf in 1989 and 1994. Circles indicate the number of animals seen along 1 km of transect, and do not necessarily reflect group size. The 1989 transects over Ningaloo Reef were longer than those of 1994.

communication). The timing of this seagrass loss is unknown, but could potentially account for the differences in dugong distribution during the two surveys.

The 1989 and 1994 surveys provide a good indication of the distribution of dugongs in Shark Bay in winter. Comparable data are not available for summer. The Faure Sill (in the centre of Block 3; Figs 1, 2) is known to be an important summer feeding area (Anderson 1986). Between one-third and one-half of the Shark Bay dugong population was using this area when it was surveyed twice in the summer of 1990–91 (Marsh *et al.* 1994). The summer distribution of the total Shark Bay dugong population, however, is not known as the entire bay has not been surveyed during this season, which is characterised by long periods of strong winds and poor survey conditions.

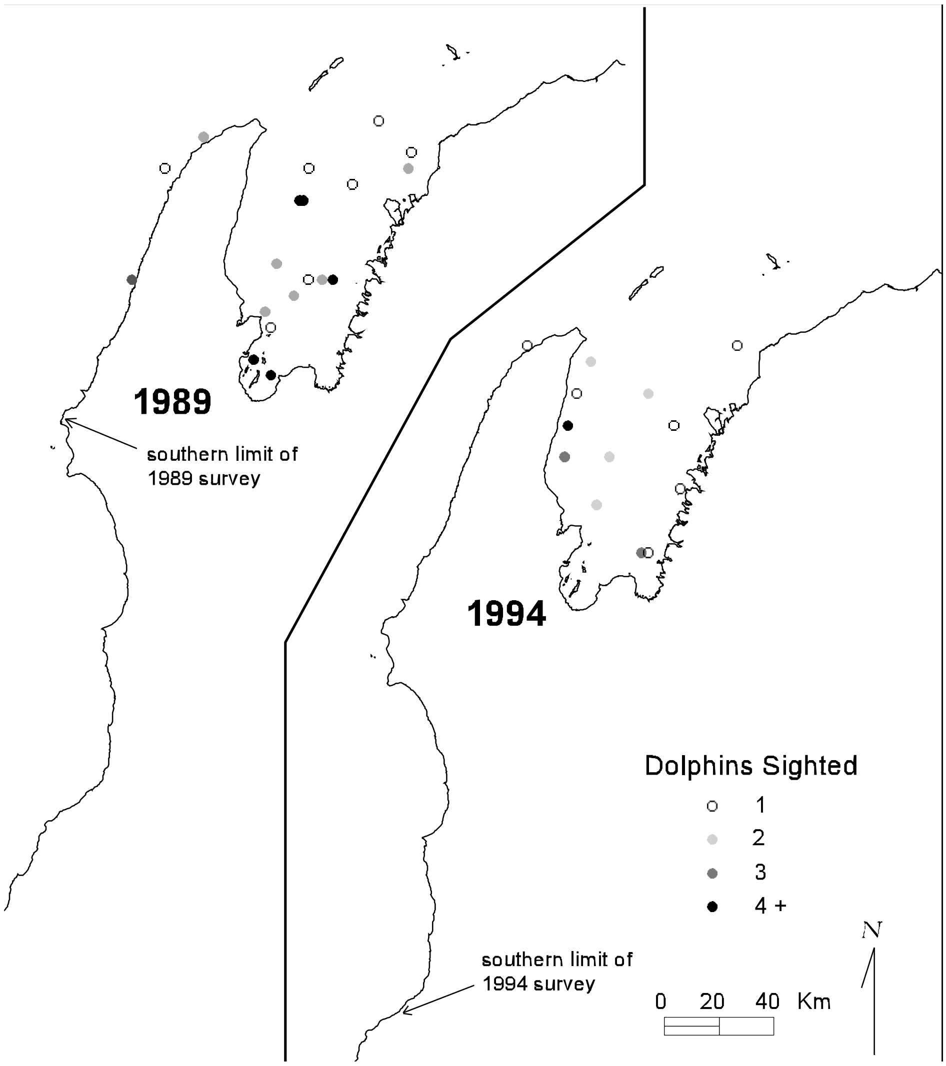

Fig. 9. Dolphin sightings in Ningaloo Reef and Exmouth Gulf in 1989 and 1994. Circles indicate the number of animals seen along 1 km of transect, and do not necessarily reflect group size. The 1989 transects over Ningaloo Reef were longer than those of 1994.

Anderson (1982, 1986) noted that the distribution of dugongs in Shark Bay varied seasonally, the dugongs being driven from their preferred feeding grounds in the east of the bay by low water temperatures in winter. The dugongs were thought to take refuge in the warmer waters of the western bay, particularly along the eastern shores of Dirk Hartog Island (Anderson 1982). The winter survey of 1989 (the first to cover all the bay) found that many of the dugongs actually remained in the east of the bay (Fig. 3). This area had relatively warm water, and 96% of dugongs were sighted in areas with water no colder than 18°C. Indirect evidence suggests that 18–19°C is a critical temperature for dugong thermoregulation (Anderson 1986; Preen 1989, 1993). In 1994, 86% of dugongs seen were in water no colder than 18°C, but very few dugongs were found in the east of the bay (Fig. 3). Taken together, these data (in the absence of a

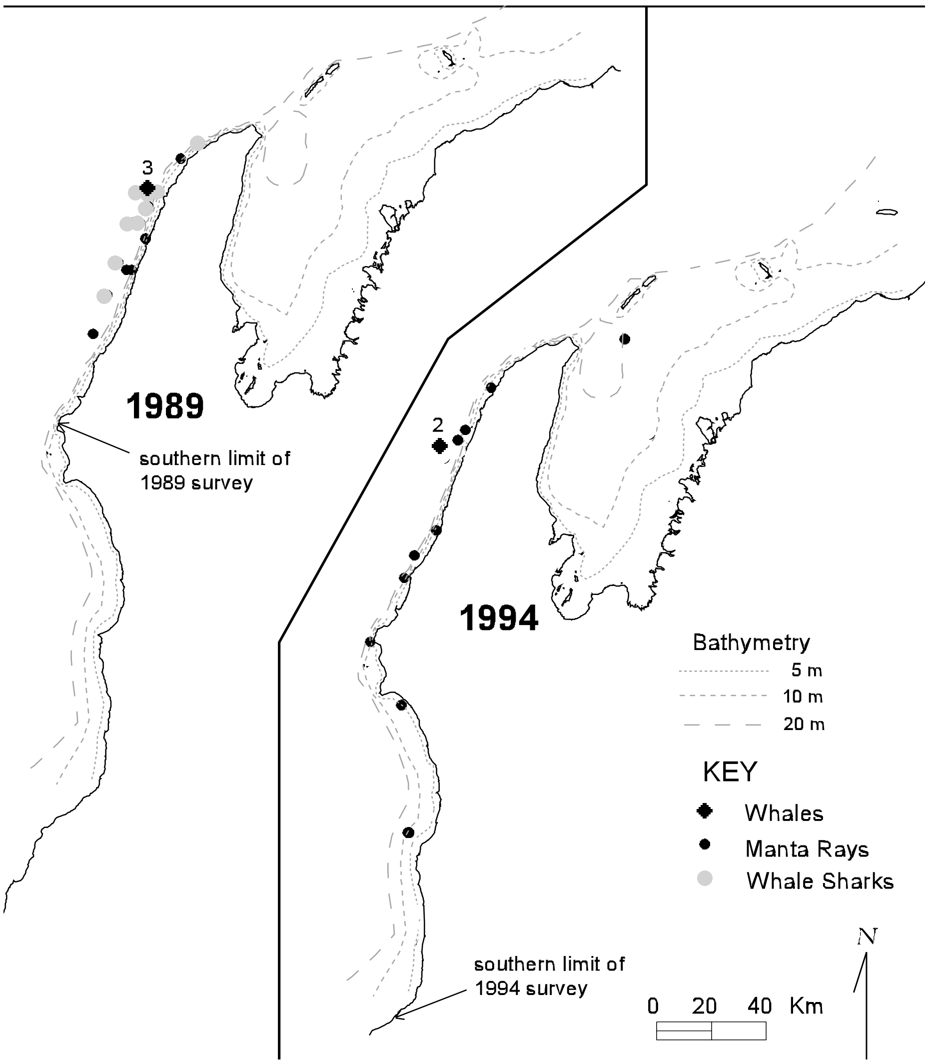

Fig. 10. Bathymetry and the distribution of whale, whale shark and manta ray sightings in Ningaloo Reef and Exmouth Gulf in 1989 and 1994. The 1989 transects over Ningaloo Reef were longer than those of 1994.

complete summer survey of the bay) suggest that the seasonal movement of the majority of dugongs in Shark Bay is from the shallow banks dominated by tropical seagrass in the eastern (Faure Sill) and southern (Henri Frecinet Harbour) parts of the bay in summer into deeper, relatively warmer waters in winter.

The proportion of the dugong population that was calves (19% in 1989 and 16·6% in 1994) is relatively high compared with surveys done in other areas (1·4–20·4%; table 4 in Marsh *et al.* 1994). The difference between surveys probably reflects the imprecision of the definition of a calf: ‘a substantially smaller animal in close association with another’. Previous shoreline surveys in Shark Bay have returned calf counts of 11–12% (Anderson 1982) and 10·4% (Anderson 1986). These estimates differ substantially from our estimates, but it is not possible to determine whether the disparity is due to definitional differences or whether they reflect temporal variation in reproductive success.

Turtles

Whereas turtles were abundant in Shark Bay (more than 8400 in 1994), and their density (0·57 km^{-2}) was comparable to densities recorded from areas of similar latitude in south-eastern Queensland, they occurred at a density lower than that in more tropical areas of Queensland and the Torres Strait (Table 5). Turtle density, at least in eastern Australia, appears to correlate with latitude (Table 5).

Green turtles are the most common species in Shark Bay (Department of Conservation and Land Management 1994), and the identifications made during the 1994 survey support this assessment. A few loggerhead turtles were also seen. The proportion of loggerheads would probably increase in summer, when breeding turtles arrive from other areas to nest at the rookery at the northern tip of Dirk Hartog Island (Prince 1994*a*), and when resident green turtles are expected to migrate out of the bay to breed.

The 1989 distribution of turtles in Shark Bay corresponds with the pattern of surface water temperatures, with most turtles avoiding water colder than about 18°C (Fig. 4). This pattern appears to break down in 1994, as a considerable concentration of turtles occurred in the cool waters close to shore along the Wooramel Bank (Fig. 4). This apparent anomaly may be explained by the timing of the capture of the satellite images used to derive water temperatures. At 0717 hours, when the 1994 image was captured, the shallow waters where these turtles occurred (33% of turtles east of the Peron Peninsula were in water <3 m deep) would have been cold from the previous night. However, under suitable daytime conditions of light breezes and clear skies (as experienced during the aerial survey), shallow waters can warm considerably. As all the Wooramel Bank was surveyed in the afternoon in 1994, it is probable that at least the

Table 5. Densities of turtles and dolphins recorded during aerial surveys of areas by the same technique

References: 1, Marsh, Saalfeld and Preen (unpublished data); 2, Marsh, Breen and Preen (unpublished data); 3, Marsh and Saalfeld (1989*b*); 4, Marsh, Kwan and Lawler (unpublished data); 5, Marsh and Lawler (unpublished data); 6, Marsh and Saalfeld (unpublished data); 7, Marsh *et al.* (1997); 8, this study

Location	Latitude (°S)	Year	Area (km^2)	Density (km^{-2}) ± s.e.		Reference
				Turtles	Dolphins	
South-eastern Queensland	25–27	1988	9170	0·32 ± 0·04	–	1
Southern Great Barrier Reef	15–25	1986/87	39396	0·64 ± 0·04	0·17 ± 0·01	2
		1992	39396	0·85 ± 0·13	0·30 ± 0·04	2
Northern Great Barrier Reef	11–15	1985	31288	1·03 ± 0·081	0·21 ± 0·082	3 (turtles); 4 (dolphins)
		1990	31288	1·46 ± 0·11	0·16 ± 0·02	4
Mornington Island area	17	1991	8848	0·95 ± 0·15	0·09 ± 0·02	5
Torres Strait	9–11	1987	30533	1·43 ± 0·16	–	6
		1991	30560	2·13 ± 0·17	0·07 ± 0·02	7
Shark Bay	25–27	1989	14906	0·43 ± 0·05	0·19 ± 0·03	8
		1994	14906	0·57 ± 0·05	0·14 ± 0·02	8
Exmouth	22	1989	3180	1·42 ± 0·28	0·16 ± 0·04	8
		1994	3180	1·02 ± 0·22	0·09 ± 0·03	8
Ningaloo	22–23	1989	555	4·51 ± 0·47	0·18 ± 0·06	8
		1994	869	4·90 ± 0·83	–	8

surface waters in this area were warmer than indicated by the early morning satellite image, so the distribution of turtles was probably not anomalous. The 1989 image was captured in the afternoon.

Dolphins

The 1989 and 1994 surveys indicate a population of 2000–3000 dolphins in Shark Bay, most being bottlenose. The real number is likely to be higher, as these estimates make no correction for availability bias. The density of dolphins (0·14–0·19 km^{-2}) is comparable to densities estimated for the Great Barrier Reef Marine Park (0·16–0·3), and greater than for Torres Strait (0·07) and the Mornington Island area in the Gulf of Carpentaria (0·09) (Table 5).

Other taxa

Post-war whaling occurred in northern Shark Bay between 1950 and 1962, by which time the population of humpback whales had been reduced from about 10 000 to no more than 800 (Chittleborough 1965). The number of whales using the area is now increasing, reflecting the recovery of populations of the Area IV stock (Bannister 1994). Sightings of humpback and southern right whales (*Eubalaena australis*) in Shark Bay embayments have increased in recent years (Department of Conservation and Land Management 1994), and humpback whales were common in the northern part of the bay in 1994 (Fig. 6). Manta rays were common in the Denham Sound area. Both these taxa appeared to be restricted to the areas of oceanic salinities.

Ningaloo and Exmouth

Dugongs

The density of dugongs in Ningaloo Reef and Exmouth Gulf was about half that of Shark Bay, but was comparable to the densities of dugongs recorded in other significant dugong habitats in northern Australia (table 4 in Marsh *et al.* 1994), excluding Torres Strait, where densities are similar to those in Shark Bay (Marsh *et al.* 1997). The Ningaloo–Exmouth population (approximately 2000 dugongs; Table 3) is substantial, being comparable to that of much larger areas, such as the central plus southern sections of the Great Barrier Reef Marine Park (Marsh and Saalfeld 1990; Marsh *et al.* 1996) and the eastern coast of the Red Sea (Preen 1989). On the basis of the movements of tracked dugongs in other areas (Preen, unpublished data), the dugongs probably move freely between Ningaloo Marine Park and Exmouth Gulf.

It is likely that the aerial surveys have inadequately sampled the dugong population in this region, as suitable habitat extends well beyond the northern boundary of the Exmouth survey block. The significant difference between Exmouth surveys may well be due to a net movement of dugongs across that northern boundary. The nature of the seagrass communities in this region is poorly understood (Walker and Prince 1987), although seagrasses appear to be abundant just north of Exmouth Gulf (Bowman Bishaw Gorham 1995), but uncommon in the south-east of the gulf (McCook *et al.* 1995).

Turtles

The density of turtles in Ningaloo Marine Park (4·9 ± 0·8 km^{-2}) exceeds the highest densities of turtles recorded in any survey block throughout the Great Barrier Reef Marine Park (Table 5). Only one survey block, during one of two surveys of Torres Strait, had a higher density of turtles (5·1 ± 0·7 km^{-2}; Marsh, unpublished data). The very high density of turtles in Ningaloo Marine Park may, in part, be an artefact of the particularly clear waters of the reef and lagoon. Conversely, the turbid water in much of Exmouth Gulf may account for the apparently lower density of turtles in this area. However, the density of turtles in Exmouth Gulf (1·0–1·4 km^{-2}) is still twice the value for Shark Bay, and comparable to the density of turtles in Torres Strait, the northern section of the Great Barrier Reef Marine Park (Table 5), and the best embayments in the central and southern sections of the Great Barrier Reef Marine Park (Marsh, Breen and Preen, unpublished data).

Our surveys were conducted outside the summer breeding season for sea turtles in this region (Prince 1994*b*), so we surveyed resident turtles. The relative abundance of different turtle species in Ningaloo Marine Park and Exmouth Gulf is unknown, but the different habitats in each area may favour different species. Green turtles are the most abundant species in Ningaloo Marine Park, and hawksbill turtles (*Eretmochelys imbricata*) are also present (May *et al.* 1983). This latter species is rarely detected during our aerial surveys because of its small size and close association with reefs. At the southern end of Exmouth Gulf, 566 turtles have been tagged in recent years after being stranded behind tunnel or trap nets. Juvenile green turtles were the most common (86%) followed by loggerheads (11%) and hawksbills (3%) (Prince, unpublished data). Little is known of the movements of turtles between Exmouth Gulf and Ningaloo Reef, as only three tag returns have been obtained from these turtles. One was from the southern end of Ningaloo Marine Park, one from the north-west of the gulf and one from the south-west of the gulf (Prince, unpublished data).

Dolphins

Dolphins were not common in Ningaloo Marine Park or Exmouth Gulf on either survey. However, the densities of dolphins in these areas (0·09–0·18 km^{-2}; Table 3) are comparable to densities estimated for the Great Barrier Reef Marine Park (0·16–0·3) and Torres Strait (0·07) (Table 5).

The species composition of dolphins varied substantially between surveys, although with ‘unidentified’ dolphins making up 22–42% of sightings, such apparent change may be an artefact. As in Shark Bay, bottlenose dolphins were the most common, although *S. chinensis* is relatively more common in this more tropical area.

Other taxa

Ningaloo Marine Park, at least the northern half, is an important feeding area for whale sharks (Taylor 1989, 1994*a*, 1994*b*) and manta rays (Fig. 10). A tourist industry, based out of Exmouth, has developed around the whale sharks since 1989. The presence of the whale sharks is apparently seasonal, although the end of the season is variable. Whale sharks were common during the 13 July survey in 1989, but absent during the 22–23 June survey in 1994. Although it is possible that this difference was due to the shorter transects in 1994, local tourist operators reported that the whale sharks had left the area three weeks before the 1994 survey.

Humpback whales migrate through the waters immediately adjacent to Ningaloo Reef and sometimes aggregate adjacent to the reef (May *et al.* 1983). Whaling operations commenced at this location in 1913 (May *et al.* 1983) and occurred on a large scale (up to 600 taken annually) between 1949 and 1955 (Chittleborough 1965).

Management Considerations

In July 1989, 57·4% of dugongs sighted in Shark Bay were outside the Shark Bay Marine Park. In June 1994, the value was 50·7%. In 1989 and 1994, respectively, 43 and 27% of the recorded turtles were not in the Marine Park. At the same times, 48·6 and 32·4% of dolphins were outside the Marine Park. Similarly, nearly all the whales and most of the manta rays occurred out of the Marine Park. Taken together, the winter distribution of Shark Bay’s megafauna presents a strong case for the extension of the Marine Park boundary to include the northern and western areas of the bay. These areas are included in the Shark Bay World Heritage Area.

The current boundary of the Shark Bay Marine Park was substantially determined by the distribution of existing trawling grounds (Department of Conservation and Land Management 1994), the apparent aim being to avoid conflicts over resource use by locating the boundary outside established trawling areas. In using this criterion, however, the habitats of many important species have been deprived of protection, and the Marine Park has a complicated boundary that would be difficult to police. The Marine Park should be expanded to enclose all of Shark Bay. To simplify State–Commonwealth collaboration in meeting the obligations of the

World Heritage Convention, it would be appropriate for the Marine Park boundary to shadow the marine boundary of the World Heritage Area (Fig. 1). The difference in the World Heritage and Marine Park boundaries of the Great Barrier Reef in Queensland is an ongoing problem for management agencies.

Expansion of the Shark Bay Marine Park to the World Heritage Area boundary would not necessarily exclude trawling, as the General Use Zone, which is currently applied to most of the Marine Park, allows this form of fishing (Department of Conservation and Land Management 1994). Inclusion of trawl grounds within the park may help ensure that fishing practices are ecologically sustainable by facilitating investigations into the effects of trawling on benthic communities and by encouraging the use of turtle excluder devices (TEDs) (Committee on Sea Turtle Conservation *et al.* 1990) in trawl nets.

The abundance of whales in the Carnarvon area in the north of Shark Bay highlights the potential for this former whaling town to develop a whale-watching industry. This has occurred in other areas in Australia, including Perth and Albany in Western Australia, and Hervey Bay, Moreton Bay and the Whitsunday Islands in eastern Australia (Postle and Simmons 1994). Experience from some of these areas suggests that management agencies need to anticipate such developments and be pro-active in their planning if the industry is to develop without having an impact on the whale population. Inclusion of this area in the Shark Bay Marine Park would allow Special Purpose Zones to be established, specifically to manage whale-watching activities (Government of Western Australia 1994).

It is apparent that the distribution of dugongs in Shark Bay differs between winter and summer. Turtles and other species may show a similar pattern. Given the multiple-use nature of the Shark Bay Marine Park (Department of Conservation and Land Management 1994), the effective management of Shark Bay will require more-detailed information on the seasonal distribution and movement patterns of these threatened species. The mapping of important habitats should also have a high priority. As a result of the 1989 aerial survey, an extensive deep-water seagrass meadow was discovered near the eastern concentration of dugongs, in Survey Block 5 (Anderson 1994). The 1994 distribution of dugongs around Denham Sound (Figs 1, 3) suggests the presence of further deep-water seagrasses.

Almost all of Exmouth Gulf is covered by petroleum exploration permits, and this area is also the focus of a major prawn trawl fishery (Marine Parks and Reserves Selection Working Group 1994). Exmouth Gulf is also an important habitat for dugongs and turtles. The Muiron Islands, at the northern edge of the gulf, have the second-largest loggerhead turtle rookery in Western Australia (Prince 1993). There is clearly a need to achieve a sustainable balance between utilisation and conservation in this area. The recent recommendation, that the eastern side of Exmouth Gulf be considered for reservation as a marine protected area (Marine Parks and Reserves Selection Working Group 1994), should be supported strongly as a first step.

The delineation of Exmouth Gulf used in these surveys was determined by logistical constraints rather than ecological boundaries. The coastal waters north of the surveyed area are comparatively unknown, but there is every likelihood that they support important populations of dugongs, dolphins and turtles (Prince *et al.* 1981; Prince 1986). Extensive deep-water (12–18 m) seagrass meadows have been located immediately to the north of Exmouth Gulf (between Sunday and Thevenard Islands; Bowman Bishaw Gorham 1995), suggesting the presence of important dugong habitat. Surveys of fauna and habitats along the extensive tropical coastline of Western Australia are required. This need is most pronounced in the North West Shelf region, where the oil- and gas-extraction industry is developing rapidly (Department of Minerals and Energy 1994).

Concluding Comment

The population of dugongs in Shark Bay is unusual and of considerable international significance because of its large size, the low level of human predation and incidental mortality, and the presumed low level of habitat disturbance. With conservative management, this population has an almost uniquely stable future. As such, it will be a valuable reference point with which to compare, through time, other important populations that are subjected to greater levels of hunting, fishing-net entanglements and habitat disturbance.

Acknowledgments

This work was funded by the Western Australian Department of Conservation and Land Management and the Commonwealth Department of Environment, Sport and Territories. Other observers during the aerial surveys were Keith Saalfeld and Andrew Williams (1989) and Heidi Westlake and Bill Cuthbert (1994). Richard Stovold and Andrew Buchanan provided the thermal imagery and Nina Morrisette helped with its manipulation.

References

Anderson, P. K. (1982). Studies of dugongs at Shark Bay, Western Australia. I. Analysis of population size, composition, dispersion and habitat use on the basis of aerial survey. *Australian Wildlife Research* **9**, 69–84.

Anderson, P. K. (1986). Dugongs of Shark Bay, Australia—seasonal migration, water temperature, and forage. *National Geographic Research* **2**, 473–490.

Anderson, P. K. (1994). Dugong distribution, the seagrass *Halophila spinulosa*, and thermal environment in winter in deeper waters of eastern Shark Bay, Western Australia. *Wildlife Research* **21**, 381–388.

Bannister, J. L. (1994). Continued increase in humpback whales off Western Australia. *Reports of the International Whaling Commission* **44**, 309–310.

Bowman Bishaw Gorham (1995). North West Shelf Environmental Resource Atlas. Report prepared for BHP Petroleum Pty Ltd.

Chittleborough, R. G. (1965). Dynamics of two populations of the humpback whale *Megaptera novaeangliae* (Borowski). *Australian Journal of Marine and Freshwater Research* **16**, 33–128.

Committee on Sea Turtle Conservation, Board on Environmental Studies and Toxicology, Board on Biology, Commission on Life Sciences and National Research Council (1990). 'Decline of Sea Turtles: Causes and Prevention.' (National Academy Press: Washington, DC.)

Department of Arts, Sport, the Environment, Tourism and Territories (1990). Nomination of Shark Bay, Western Australia by the Government of Australia for inclusion in the World Heritage List. Department of Arts, Sport, the Environment, Tourism and Territories, Canberra.

Department of Conservation and Land Management (1989). Ningaloo Marine Park (State waters) Management Plan 1989–1999. Department of Conservation and Land Management, Perth.

Department of Conservation and Land Management (1994). Shark Bay Marine Reserves Draft Management Plan. National Parks and Nature Conservation Authority, Perth.

Department of Environment, Sport and Territories (1995). World Heritage Information Kit. Shark Bay, Western Australia. Department of Environment, Sport and Territories, Canberra.

Department of Minerals and Energy (1994). North West Shelf, oil and gas. Petroleum Operations Division, Western Australian Department of Minerals and Energy, Perth.

Government of Western Australia (1994). 'New Horizons in Marine Management.' (Government of Western Australia: Perth.)

Jolly, G. M. (1969). Sampling methods for aerial censuses of wildlife populations. *East African Forestry Journal* **34**, 46–49.

Logan, S. H., and Cebulski, D. E. (1970). Sedimentary environments of Shark Bay, Western Australia. *Memoirs of the American Association of Petroleum Geologists* **13**, 1–37.

Marine Parks and Reserves Selection Working Group (1994). A representative marine reserve system for Western Australia. Report of the Marine Parks and Reserves Selection Working Group. Department of Conservation and Land Management, Perth.

Marsh, H., and Rathbun, G. B. (1990). Development and application of conventional and satellite radio tracking techniques for studying dugong movements and habitat use. *Australian Wildlife Research* **17**, 83–100.

Marsh, H., and Saalfeld, W. K. (1989*a*). Distribution and abundance of dugongs in the northern Great Barrier Reef Marine Park. *Australian Wildlife Research* **16**, 429–440.

Marsh, H., and Saalfeld, W. K. (1989*b*). Aerial surveys of sea turtles in the northern Great Barrier Reef Marine Park. *Australian Wildlife Research* **16**, 239–249.

Marsh, H. D., and Saalfeld, W. K. (1990). The distribution and abundance of dugongs in the Great Barrier Reef Marine Park south of Cape Bedford. *Australian Wildlife Research* **17**, 511–524.

Marsh, H., and Sinclair, D. F. (1989*a*). Correcting for visibility bias in strip transect aerial surveys of aquatic fauna. *Journal of Wildlife Management* **53**, 1017–1024.
Marsh, H., and Sinclair, D. F. (1989*b*). An experimental evaluation of dugong and sea turtle aerial survey techniques. *Australian Wildlife Research* **16**, 639–650.
Marsh, H., Prince, R. I. T., Saalfeld, W. K., and Shepherd, R. (1994). The distribution and abundance of the dugong in Shark Bay, Western Australia. *Wildlife Research* **21**, 149–161.
Marsh, H., Corkeron, P., Lawler, I., Lanyon, J., and Preen, A. (1996). The status of the Dugong in the southern Great Barrier Reef Marine Park. Research Publication No. 41, Great Barrier Reef Marine Park Authority.
Marsh, H., Harris, A. N. B., and Lawler, I. R. (1997). Is the dugong fishery in Torres Strait sustainable at current harvest levels. *Biological Conservation* (in press).
May, R. F., Lenanton, R. C. J., and Berry, P. F. (1983). Ningaloo Marine Park. Report and recommendations to the Marine Park Working Group. National Parks Authority, Report No. 1, Perth.
McCook, L. J., Klumpp, D. W., and McKinnon, A. D. (1995). Seagrass communities in Exmouth Gulf, Western Australia: a preliminary survey. *Journal of the Royal Society of Western Australia* **78**, 81–87.
McMillin, L. M., and Crosby, D. S. (1984). Theory and validation of the multiple window sea surface temperature technique. *Journal of Geophysical Research* **89**, 3655–3661.
Norton-Griffiths, M. (1978). 'Counting Animals Handbook No. 1.' (Serengeti Biological Monitoring Programme African Wildlife Leadership Foundation: Kenya).
Pearce, A. F., and Walker, D. I. (Eds) (1991). The Leeuwin current: an influence on the coastal climate and marine life of Western Australia. *Journal of the Royal Society of Western Australia* **74**.
Postle, D., and Simmonds, M. (Eds) (1994). 'Encounters with Whales '93. A Conference to Further Explore the Management Issues Relating to Human/Whale Interactions.' Workshop Series No. 20. (Great Barrier Reef Marine Park Authority: Townsville.)
Preen, A. (1989). Dugongs. Vol. 1. The status and conservation of dugongs in the Arabian Region. Meteorology and Environmental Protection Administration Coastal and Marine Management Series. Report No. 10, Jeddah.
Preen, A. R. (1993). Interactions between dugongs and seagrasses in a subtropical environment. Ph.D. Thesis, James Cook University of North Queensland, Townsville.
Prince, R. I. T. (1986). Dugong in northern waters of Western Australia 1984. Technical Report No. 7. Department of Conservation and Land Management, Perth.
Prince, R. I. T. (1993). Western Australian marine turtle conservation project: an outline of scope and an invitation to participate. *Marine Turtle Newsletter* **60**, 8–14.
Prince, R. I. T. (1994*a*). Shark Bay World Heritage Area: an important loggerhead nesting site. *Marine Turtle Newsletter* **67**, 5–6.
Prince, R. I. T. (1994*b*). Update: sea turtles in Western Australia. *Marine Turtle Newsletter* **64**, 18–19.
Prince, R. I. T., Anderson, P. K., and Blackman, D. (1981). Status and distribution of dugongs in Western Australia. In 'The Dugong: Proceedings of a Seminar/Workshop Held at James Cook University 8–13 May, 1979'. (Ed. H. Marsh.) pp. 67–87. (James Cook University of North Queensland: Townsville.)
Ross, G. J. B., Heinsohn, G. E., and Cockroft, V. G. (1994). Humpback dolphins *Sousa chinensis* (Osbeck, 1765), *Sousa plumbea* (G. Cuvier, 1829) and *Sousa teuszii* (Kukenthal, 1892). In 'Handbook of Marine Mammals. Vol. 5'. (Eds S. H. Ridgeway and R. Harrison.) pp. 23–42. (Academic Press: London.)
Smolker, R. A., Richards, A. F., Conner, R. C., and Pepper, J. W. (1992). Sex differences in patterns of association among Indian Ocean bottlenose dolphins. *Behaviour* **123**, 38–69.
Taylor, G. (1989). Whale sharks of Ningaloo Reef, Western Australia: a preliminary study. *Western Australian Naturalist* **18**, 7–12.
Taylor, G. (1994*a*). Gentle giants of the deep. *Australian Geographic* **34**, 93–103.
Taylor, G. (1994*b*). 'Whale Sharks. The Giants of Ningaloo Reef.' (Angus & Robertson: Sydney.)
Walker, D. I. (1989). Regional studies—seagrass in Shark Bay, the foundation of an ecosystem. In 'Biology of Seagrasses. A Treatise on the Biology of Seagrasses with Special Reference to the Australian Region'. (Eds A. W. D. Larkum, A. J. McComb and S. A. Shepherd) pp. 182–210. (Elsevier: Amsterdam.)
Walker, D. I., and Prince, R. I. T. (1987). Distribution and biogeography of seagrass species on the northwest coast of Australia. *Aquatic Botany* **29**, 19–32.
Wilson, B. R., Hancock, D. A., and Chittleborough, R. G. (1979). The Sea. In 'Environment and Science'. (Ed. B. J. O'Brien.) pp. 146–182. (University of Western Australia Press: Perth.)

Manuscript received 28 November 1995; revised 21 May 1996; revised and accepted 16 September 1996