Survey of
Crown-of-Thorns starfish and coral communities in the Dampier Archipelago, Western Australia

Survey of
Crown-of-Thorns starfish and coral communities in the Dampier Archipelago, Western Australia.

C J Simpson and K A Grey

SUMMARY

The densities of crown-of-thorns starfish, *Acanthaster planci* (L.), and live coral cover were estimated at 13 sites in the Dampier Archipelago during October 1985. Eleven sites were located on the peripheral seaward reefs of the archipelago and two on inner reefs. At most of the seaward sites two transects were surveyed; an upper-reef slope transect about 2-3 m below chart datum and a mid-reef slope transect about 7-8 m below chart datum. Although *A. planci* was relatively common on the seaward reefs, this starfish was not recorded at the inshore reef sites. The mean density of *A. planci* was 52 starfish per hectare over the surveyed area. This is within the density range for 'normal populations' of *A. planci* on coral reefs worldwide. Starfish distribution on these reefs, however, was extremely variable with mean site densities ranging from 0 to 170 starfish per hectare.

The size frequency distribution of starfish was bimodal and possibly reflects two successive 'year classes'; 1+ and 2+. If so, the mean age of the 1+ year class was 1.5-2 years and most of these smaller starfish occurred on reefs in the far western side of the archipelago. The age of these starfish also suggests that these animals recruited onto these reefs in the summer of 1983/1984. In general, these smaller starfish occurred in algal dominated habitats, were cryptic and did not prey on hard corals. In contrast starfish in the 2+ year class occurred in coral rich areas, were less cryptic and commonly preyed on scleractinian corals. Predation on *A. planci* was high, with almost half of the starfish showing signs of recent damage. Predation occurred more frequently and was more intense on smaller starfish. Overall, 96% of starfish were found in the western half of the archipelago and an eastward trend of increasing starfish size is evident. Circumstantial evidence suggests this trend may be due to conditions on the western side of the archipelago being more favourable for *A. planci* recruitment and the resultant dispersal of these recruits, rather than to variable starfish growth rates due to changes in preferred prey abundance.

Extensive reefs occur on the seaward periphery of the archipelago and are dominated by acroporid, and to a lesser extent, pocilloporid species. The tabular coral *Acropora hyacinthus* is particularly dominant on these seaward reefs. Live coral cover was significantly higher in the eastern half of the archipelago and on upper seaward reef slopes. Some parts of these reefs had a live coral cover of over 70%. In contrast, live coral cover on reefs in the western side of the archipelago ranged from about 2-30%. The low cover of coral on Sailfish Reef (~4%) is anomalous. It is postulated that persistent predation of juvenile corals by a small population of *A. planci* on Sailfish Reef is responsible for the slowness of recovery of this reef since 1975. A small aggregation of starfish was causing considerable damage to the reef at Nelson Rocks during October 1985. *A. planci* predation appears to be responsible for the marked reduction in live coral on this reef between 1983-1985.

Observations of *A. planci* on Western Australian coral reefs suggest that, apart from the reefs off the Pilbara coast, this starfish is rare. South of latitude 22° S, sub-optimal temperatures during the assumed breeding season of *A. planci* may restrict larval development, and unfavourable current patterns may limit southward dispersal of larvae from breeding populations on more northern reefs. Thus recruitment of *A. planci* onto Ningaloo Reef may be confined principally to immigration of individuals from populations further north. Conversely, supra-optimal temperatures on the predominantly shallow, intertidal coral reefs off the Kimberly coast (north of latitude 17° S) during summer, may inhibit larval development and restrict the summer distribution of *A. planci* to the limited sub-tidal reefs that occur in this region, thereby keeping population numbers low.

TABLE OF CONTENTS
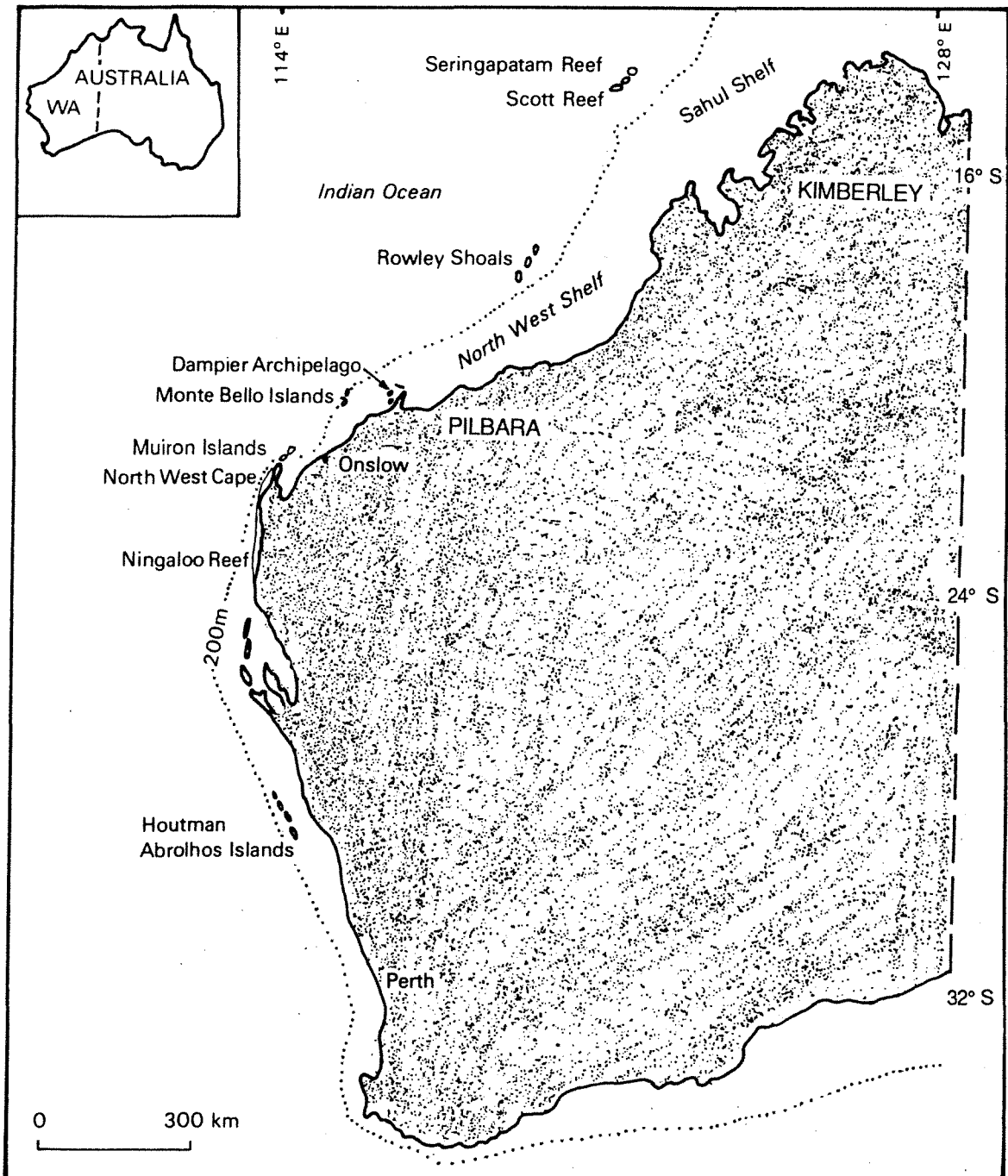
LIST OF FIGURES

LIST OF TABLES

Figure 1. Location map of Western Australia.

1. INTRODUCTION

The crown-of-thorns starfish, *Acanthaster planci* (L.), is a well known predator of scleractinian corals and large aggregations of this asteroid have caused considerable damage to coral reefs in the Indo-Pacific region over the last twenty five years (Potts, 1981; Moran, 1986). In Australia, outbreaks of *A. planci* have caused extensive damage to parts of the Great Barrier Reef since at least the early 1960s (Barnes and Endean, 1964). These outbreaks were confined mainly to the central section of the Great Barrier Reef, between latitudes 15° - 20° S (Potts, 1981; Moran, 1986). At present the cause of these outbreaks is unknown and is the subject of continuing scientific debate and intensive scientific research (Moran, 1986; Zann, 1987; Zann & Eager, 1987).

Considerably less is known about the biology and ecology of *A. planci* on Western Australian coral reefs. Studies of the population dynamics of this starfish were conducted by the Western Australian Museum at Kendrew Island in the Dampier Archipelago between 1972-1974 (Fig. 1; Wilson and Marsh, 1974; 1975; Wilson *et al.* 1974). More recently a survey was conducted on several reefs on the western side of the archipelago in April 1987 (Johnson and Stoddart, 1988). Occasional sightings of *A. planci* have been reported at other tropical coral reefs in Western Australia. These include Ningaloo Reef, Rowley Shoals, Seringapatam and Scott Reefs (Marsh, 1986; L M Marsh, pers. comm.), reefs near Onslow (P. Chalmers, pers. comm.), the Monte Bello Islands (J. Carver, pers. comm.) and the Muiron Islands near North West Cape (S. King, pers. comm; Fig. 1). To date, *A. planci* has not been recorded on the temperate coral reefs at the Houtman Abrolhos Islands.

Preliminary data on the reproductive biology of *A. planci* in the Dampier Archipelago, suggest that spawning occurs over an extended period during the austral summer. This was inferred from the disappearance of gonads between October 1972 and February 1973, and from observations of spontaneous release of gametes from excised gonads in October 1973 and February 1974 (Wilson and Marsh, 1975).

During the present study the gonads of four *A. planci* were punctured inadvertently, causing the release of creamy-yellow eggs. The colour of these eggs suggest that these starfish were reproductively mature (Henderson and Lucas, 1971), and therefore similar to the reproductive state of starfish examined in October 1972 and 1973 by Wilson and Marsh.

An apparent increase in the number of *A. planci* was noticed by the authors on some reefs on the western side of the Dampier Archipelago in early 1983. A simultaneous decline in live coral cover and 'health' of corals on the upper seaward reef slope at Nelson Rocks had also been observed during coral growth studies conducted at this site since early 1982 (Simpson, 1985; 1988; Fig. 2). A preliminary survey of three 100 m x 20 m transects at Nelson Rocks in August 1983 (site 4 in Fig. 2) recorded a mean of 4.5 *A. planci* per 1000 m². Mean live coral cover was estimated to be approximately 65%. Twenty five starfish were recorded on one of these transects. Three 20 minute swims over different parts of this reef on the same day yielded starfish counts of 0, 8 and 11. These and further observations by the authors at numerous other locations throughout the Dampier Archipelago during 1983 and 1984, suggested that *A. planci* were concentrated on the western side of the archipelago where live coral cover appeared to be low in comparison to the eastern side.

Recent studies of *A. planci* aggregations and their long-term effect on coral reefs have been hampered by a lack of historical data on 'natural' fluctuations of starfish populations and community structure of coral reefs. These data, if available, provide a basis from which changes in reef communities can be measured and their significance, in relation to 'natural' variations, assessed. The objective of this survey was to determine *A. planci* abundance and live coral cover at selected sites in the Dampier Archipelago as baseline data for future reference. This was considered important as this area appears to be the only coral reef system in Western Australia where *A. planci* is relatively common (Wilson and Stoddart, 1987).
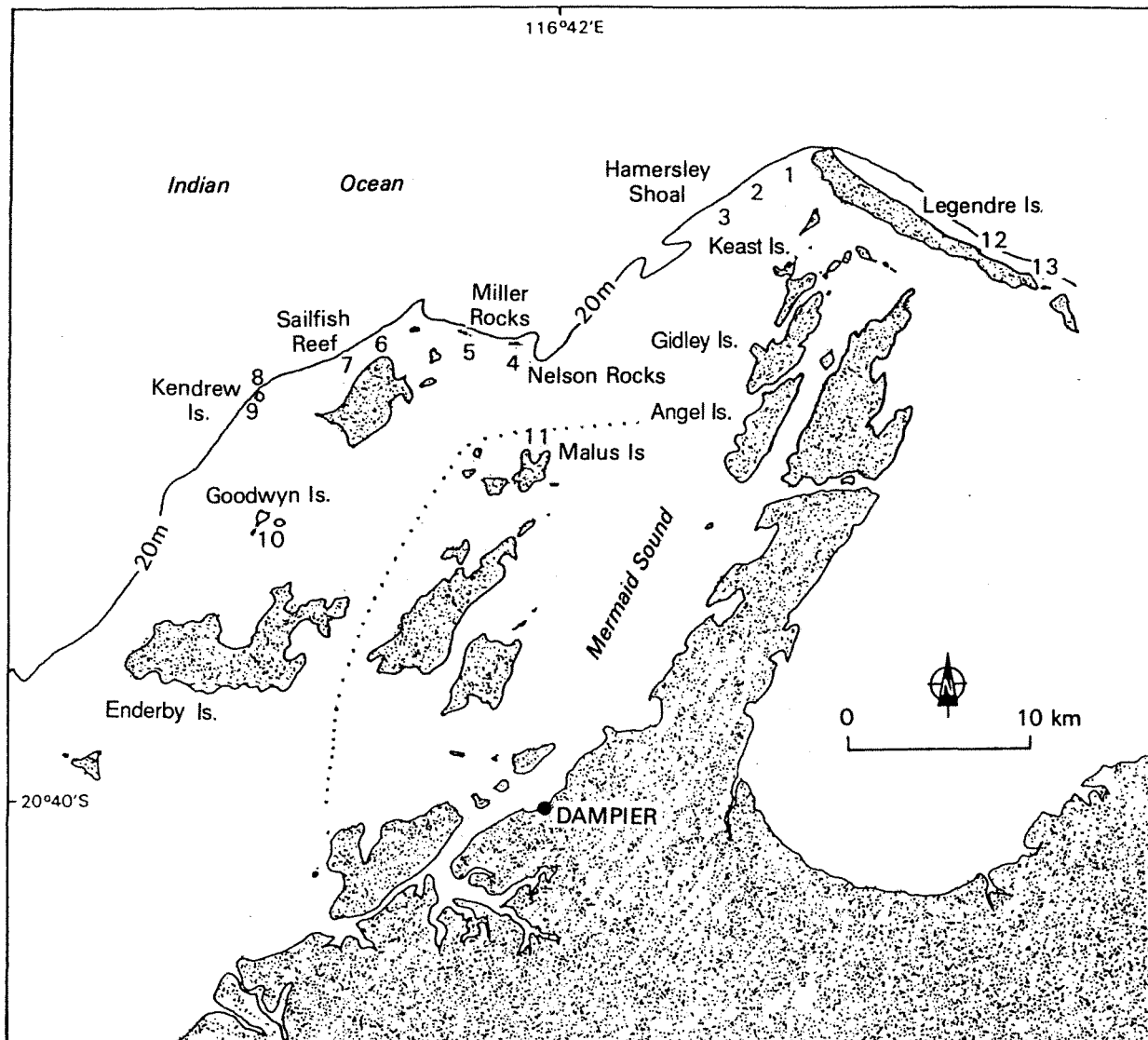
2

Figure 2. Location map of the Dampier Archipelago. Numbers refer to the approximate position of the study sites and the dotted line approximately delineates the inner reefs of the archipelago.

2. MATERIALS AND METHODS

2.1 Study sites

Thirteen study sites were selected. Eleven sites were located on peripheral seaward reefs of the Dampier Archipelago and two (10 and 11) on fringing reefs within the archipelago (Fig. 2). The approximate locations of the sites on the seaward reefs were selected randomly (except sites 4, 8 and 9) and where possible, the shallower transect at each site was positioned near a prominent bathymetric or topographic feature identified from aerial photographs (except sites 1, 2 and 3 where suitable aerial photographs were not available; Table 1). This procedure enabled relatively accurate ($\pm$ 25 m) position fixing of transect locations for future reference (Fig. 3). Site 4 was located at Nelson Rocks where the limited survey was undertaken in August 1983. Sites 8 and 9 were positioned in the vicinity of the north and west sector study sites respectively, of Wilson and Marsh (1974; 1975).

The bias towards seaward reefs was to enable comparisons to be made with the data of Wilson and Marsh (1974; 1975) who studied the temporal variation in abundance of *A. planci* on seaward reefs at Kendrew Island between 1972-1974. Furthermore, the results of a survey of corals and associated invertebrates (including echinoderms) in the Dampier Archipelago by Marsh (1978), and casual observations by the authors during 1981-1984 on reefs throughout the archipelago, suggested that *A. planci* were uncommon on inshore reefs. However, to provide quantitative data on this assumption, two sites were located on fringing reefs near Goodwyn and Malus Islands (Fig. 2).

Transect locations were positioned in the following way. An echo sounder run was made at 90° to the reef crest and marker buoys were positioned in depths of about 3 m and 7 m below chart datum on the seaward reef slope. Boat traverses, of about 100 m length, were then made along these depth contours and two additional marker buoys were dropped. Beginning at these buoys, 100 m transect lines, marked off in meters with 100 mm divisions, were then laid on the seabed along each depth contour. Transects at sites 10 and 11 were located on the outer reef-flat of the fringing reefs and transects at sites 12 and 13 were located on the mid-seaward reef slope only. In general the deeper transect at each site was surveyed first in accordance with accepted diving practices. Details of aerial photographs used, and locations of transects in relation to traces from these photographs, are shown in Table 1 and Figure 3 respectively.

The survey was conducted in October and coincided with the timing of a reported 'pre-spawning aggregation' of *A. planci* on seaward reefs near Kendrew Island in October 1972 and 1973 (Wilson and Marsh, 1974; 1975). Thus the densities of *A. planci* recorded during this survey are possibly 'pre-spawning aggregation' densities, and therefore may not be representative of densities on these reefs at other times of the year.

2.2 Data collection

Each transect (100 m x 10 m) was surveyed by two divers on SCUBA, one recording live coral cover and the other recording the occurrence of *A. planci*. Live coral cover was estimated as the percentage of live coral intersecting the 100 m transect line (Loya, 1978), and was estimated to the nearest 10 mm. In addition, the dominant benthic community type was noted and a qualitative assessment of the 'health' (ie visual patchiness of zooxanthellae in the coral colonies present) of the corals was made.

The size frequency of live coral patches is used here as an estimate of the relative size frequency distribution of the coral colonies that intersected the transect line. Although this assumes that the coral colonies are circular and that no overlap occurs between adjacent colonies, this statistic nevertheless provides a useful approximation of the relative size frequency distribution of the coral colonies present. Comparisons of size frequency distributions of coral colonies between reefs assume that species composition is similar.

A search pattern for *A. planci* was conducted as follows. The total search area of 1000 m² for each transect was divided into eight 125 m² sectors (25 m x 5 m). A diver would swim parallel to, and 1 m from, the transect line for 25 m carefully surveying the seabed 1 m
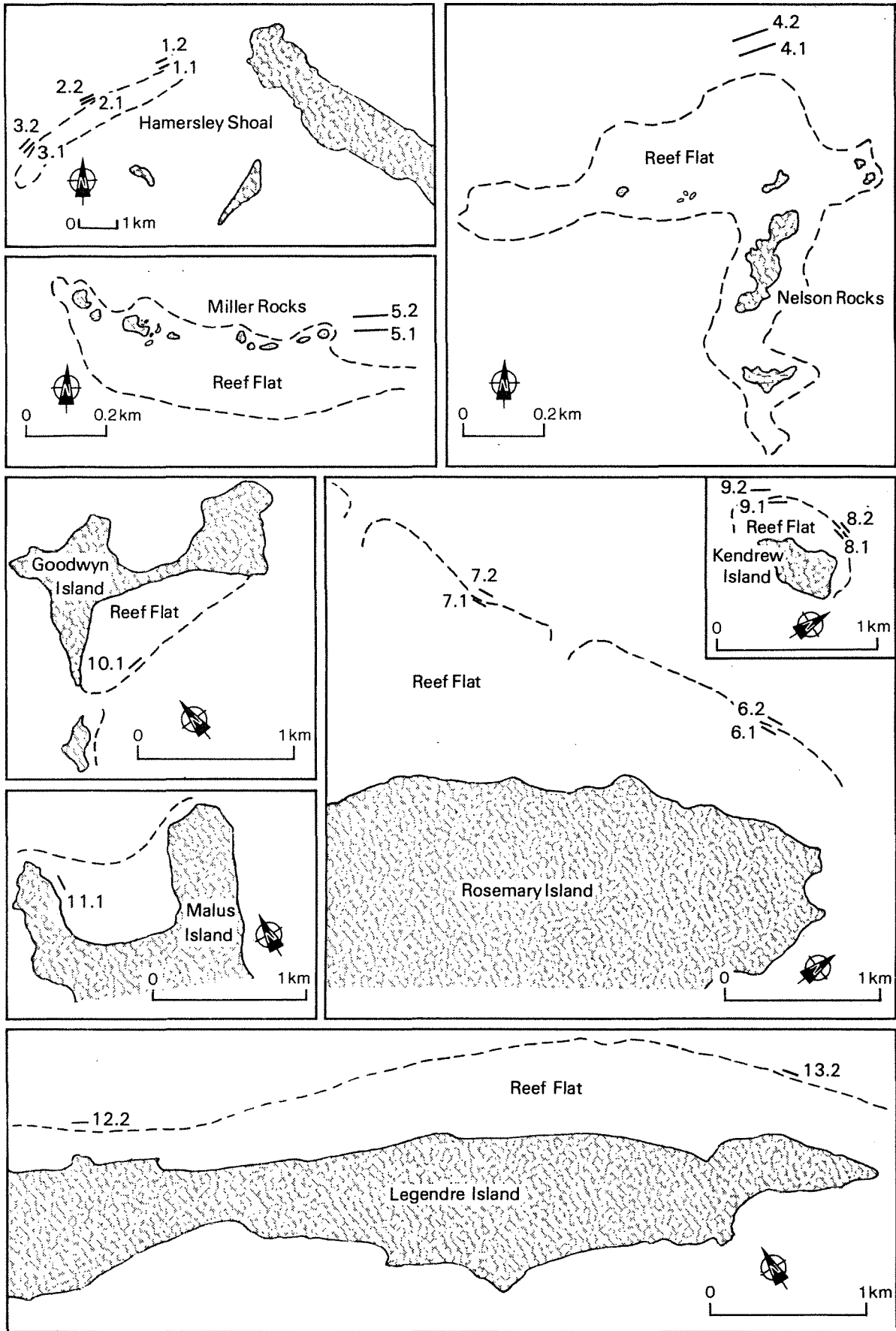
4

Figure 3. Approximate transect locations at each study site. All sites (except 1, 2 and 3) are positioned in relation to traces off aerial photographs.

either side of this imaginary line. This would then be repeated at 3 m and 5 m from the transect line. On the 5 m line, only the 25 m by 1 m section closest to the transect line would be examined. The diver would then move to the next 125 m² sector and repeat the search pattern.

If starfish were found within the search area, the following information was recorded:

(i) **Maximum diameter** (nearest 10 mm)
(ii) **In the open or hidden**
(iii) **Feeding or not**
(iv) **Food type** - if *A. planci* were feeding on coral, the genus was noted. In the case of other foods (eg coralline algae) or coral taxonomic uncertainty, specimens were collected for identification.
(v) **Number of missing or regenerating arms** - missing or regenerating arms are assumed to be the result of recent predation since regeneration of damaged arms may occur within three months (Pearson & Endean, 1969).

Where starfish were close to the boundary of the search area, a piece of 5 m long cord was attached to the transect line and the position of the starfish was measured accurately. If any part of the animal fell within 5 m of the transect line it was included in the survey. In the event of the coral cover diver finishing before the starfish diver, then this diver became a back-up starfish observer.

All divers used in this survey were proficient in underwater survey techniques and familiar with the difficulties of searching for cryptic organisms on coral reefs. Transect search times ranged from 1.5 to 3.0 man hours depending on the number of starfish present, dominant community type and the topographic complexity of the seabed.

Surface seawater temperatures ($\pm$ 0.1° C) were recorded at several sites during this survey using a Yeo-Kal Model 602 salinity-temperature meter. The time and maximum depth of each transect were also recorded and the maximum depth was adjusted to maximum depth below chart datum.

2.3 Recreational boating patterns

Aerial sightings of small boats were used in this study as an index of recreational reef usage in the Dampier Archipelago. Sightings were recorded from February 1983 to March 1988 and totalled 90 days of observations of which 64% were on weekdays and the remainder on weekends or public holidays. The number of sightings were determined for the eastern and western sides of the Dampier Archipelago. For the purposes of this study these were defined as the areas east and west of a north-south line through Mermaid Sound (Fig. 2).

3. RESULTS

3.1 Distribution and population densities

A total of 115 *A. planci* were found in the surveyed area of 2.2 ha. or approximately 52 starfish per hectare. Excluding the two sites within the archipelago (sites 10 and 11), the mean density on the seaward reef slopes was approximately 58 starfish per hectare. *A. planci* was absent at 4 sites (2, 3, 10 and 11) out of 13 and 8 transects out of the 22 surveyed. The numbers of starfish recorded for each transect are shown in Table 2. Although *A. planci* was recorded on all the peripheral seaward reefs of the archipelago that were surveyed, mean site densities were generally less than 5 per 1000 m². Relatively high mean site densities (ie $\geq$ 12 per 1000 m²) were found at three sites; on the western side of Kendrew Island (site 9), Miller Rocks (site 5) and Nelson Rocks (site 4).

The maximum density of 26 per 1000 m² was recorded at transect 9.2. Mean densities of *A. planci* for seaward reef slope sites ranged from 17 per 1000 m² at site 5, to 0 per 1000 m² at sites 2 and 3. The mean density of starfish on the eastern side of the archipelago (sites 1-3, 12 and 13; 0.6 per 1000 m²) was significantly less (Mann-Whitney U-test; p<0.0001) than the mean of 9.2 starfish per 1000 m² for seaward reef slope sites on the western side (sites 4 to 9).

In general starfish less than 200 mm in diameter were found on the deeper transects (eg transects 9.2, 5.2 in Table 3). Overall 86% of starfish in this size range were found on mid-reef slope transects in comparison to 42% of starfish over 200 mm in diameter.

6

Table 1. Details of aerial photographs used during this survey.

Site	Title	Date	Run Number (Photograph Numbers)	Photograph Number	Scale	Location
1-3	Suitable aerial photographs were not available					
4	Dampier Archipelago Turtle Study	4-12-82	3 (5424-5437)	5424	1:10000	EPA*
5	Dampier Archipelago Turtle Study	4-12-82	1 (5001-5019)	5018	1:10000	EPA
6-7	Dampier Archipelago	14-7-81	2 (5066-5096)	5092	1:25000	EPA
8-9	Dampier Archipelago	14-7-81	1 (5097-5126)	5100	1:25000	EPA
10	Dampier Archipelago	14-7-81	2 (5066-5096)	5087	1:25000	EPA
11	Dampier Archipelago	14-7-81	4 (5001-5034)	5027	1:25000	EPA
12	Dampier Archipelago	14-7-81	8 (5058-5088)	5087	1:25000	EPA
13	Dampier Archipelago	14-7-81	9 (5029-5056)	5030	1:25000	EPA

* Library of the Western Australian Environmental Protection Authority.

Table 2. Physical and biological data recorded for each transect.

Transect number	Max. depth* (m)	*A. planci* per 1000 m^2	*A. planci* with arms missing or regenerating	Live coral cover (%)	Seawater temperature ($^{\circ}$C)
1.1	3.6	0	0	2.9	24.2
1.2	8.1	1	0	20.4	24.5
2.1	3.6	0	0	58.0	-
2.2	5.5	0	0	36.8	-
3.1	1.5	0	0	63.6	-
3.2	7.2	0	0	37.7	-
4.1	4.1	15	5	24.0	23.7
4.2	6.5	9	1	7.9	-
5.1	2.7	20	9	15.4	-
5.2	6.9	14	10	1.6	-
6.1	3.1	5	1	5.5	-
6.2	7.8	3	2	2.8	24.7
7.1	2.6	4	0	2.1	-
7.2	6.4	7	2	6.4	24.3
8.1	3.8	2	1	27.8	-
8.2	8.5	0	0	8.2	-
9.1	0.6	5	2	29.9	-
9.2	6.2	26	18	1.8	-
10.1	0.5	0	0	17.6	-
11.1	0.8	0	0	70.7	-
12.2	9.4	1	1	54.4	24.5
13.2	8.0	3	2	72.6	-

* Below chart datum

3.2 Size frequency

The size frequencies of 115 *A. planci* recorded during this survey show a bimodal distribution (Fig. 4a).
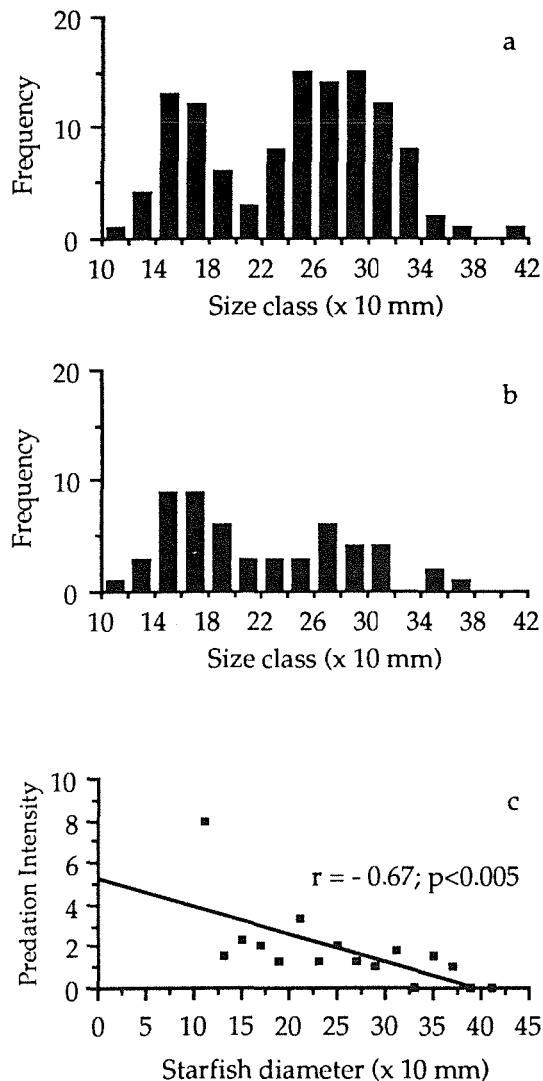

Figure 4. Size frequency distribution of: (a) *A. planci* recorded in the Dampier Archipelago in October 1985; (b) *A. planci* with missing or regenerating arms and 4 (c) predation intensity (mean number of arms missing or regenerating/starfish for each size class) on *A. planci* in relation to mean starfish diameter.

Mean diameter of all *A. planci* measured during this survey was 238 mm. Mean size of starfish with diameters less than 200 mm was 158 mm and mean diameter of starfish with diameters greater than or equal to 200 mm was 278 mm. Maximum diameters of starfish ranged from 400 mm at site 1 to 100 mm at site

6, and exhibited a general trend of decreasing size from the eastern to the western side of the archipelago (Table 3). For example, the mean diameter of starfish recorded at the most easterly site (ie site 13), on the north eastern side of Legendre Island (Fig. 2), was 307 mm. In contrast, the mean diameter of starfish on the most westerly transect (ie transect 9.2), on the western side of Kendrew Island, was 169 mm (Table 3).

3.3 Behavioural characteristics

Most *A. planci* recorded during this survey were cryptic and not feeding (Table 4) and recent feeding scars were uncommon. Overall 76% of starfish displayed a cryptic habit and 72% were not feeding. All starfish less than 200 mm in diameter were cryptic compared to 66% of starfish with diameters equal to or exceeding 200 mm. There was, however, considerable variation in starfish behaviour between sites. For example, although 71% of starfish at site 4 were cryptic, most (71%) were feeding, particularly on the undersides of the common tabular coral *Acropora hyacinthus*. The coral community at this site had a distinctly 'unhealthy' appearance (ie patchy loss of zooxanthellae) and feeding scars were common. At other sites, for example at site 9, 97% of *A. planci* were cryptic and 3% were feeding. In contrast to this, approximately 18% of starfish at site 7 were cryptic and 55% were feeding.

During this survey *A. planci* was observed preying on scleractinian corals and coralline algae. The frequency of predation of different prey is shown in Figure 5 and indicates that scleractinian corals were the principal prey of the starfish that were observed feeding. *Acropora* colonies were the most frequently predated and in particular, the tabular coral *Acropora hyacinthus*. This coral is the dominant species on the upper seaward reef slopes of the Dampier Archipelago. At sites where live coral cover was low (eg sites 6 and 7, Table 2) predation was less specific. For example, at site 7, where mean live coral cover was about 4%, 4 genera of corals (ie *Goniastrea*, *Montastrea*, *Porites* and *Acropora*) and coralline algae were observed being eaten by 6 starfish. Most of these corals were small colonies, less than 50 mm in diameter.

Table 3: Size of individual *A. planci* in relation to their location within the Dampier Archipelago. Transects are arranged from east to west.

Class size (mm)	13.2	12.2	1.2	4.1	4.2	5.1	5.2	6.1	6.2	7.1	7.2	8.1	9.1	9.2	Total
100-119									1						1
120-139							1		1					2	4
140-159		1					1	1						10	13
160-179						2	2							8	12
180-199				1			2							3	6
200-219				2									1		3
220-239						1	4	1				1	1		8
240-259				1		7	3			1	1		1	1	15
260-279				2		5		1		1	1	1	2	1	14
280-299	1			3	4	2	1		1		3				15
300-319	1			1	3	1	1	1		1	2			1	12
320-339				3	2	2				1					8
340-359	1			1											2
360-379				1											1
380-399															0
400-419			1												1
Mean	307	150	400	281	301	254	220	212	167	290	281	250	240	169	
SD	31	-	-	57	14	43	45	75	99	36	20	28	21	40	

Table 4. Behavioural characteristics and feeding habit of *A. planci* recorded during this survey.

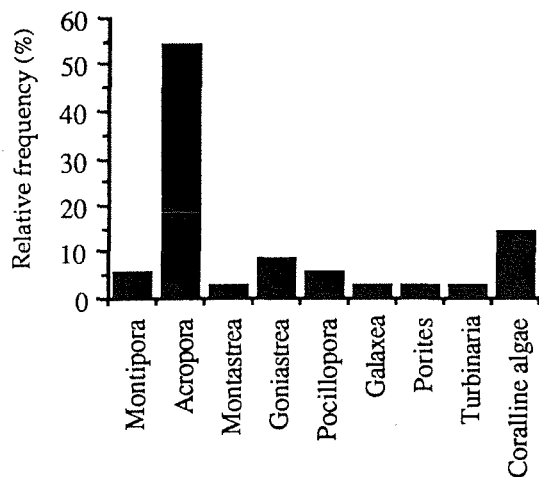| Site	Cryptic	Non-cryptic	Feeding	Non-feeding	Total
1.1	0	0	0	0	0
1.2	0	1	1	0	1
2.1	0	0	0	0	0
2.2	0	0	0	0	0
3.1	0	0	0	0	0
3.2	0	0	0	0	0
4.1	13	2	10	5	15
4.2	4	5	7	2	9
5.1	16	4	3	17	20
5.2	11	3	2	12	14
6.1	4	1	1	4	5
6.2	2	1	0	3	3
7.1	0	4	3	1	4
7.2	2	5	3	4	7
8.1	1	1	1	1	2
8.2	0	0	0	0	0
9.1	4	1	1	4	5
9.2	26	0	0	26	26
10.1	0	0	0	0	0
11.1	0	0	0	0	0
12.2	1	0	0	1	1
13.2	3	0	0	3	3
Total	87	28	32	83	115
(%)	76	24	28	72	100

Figure 5. Frequency of predation of different scleractinian coral genera and coralline algae by *A. planci*.

3.4 Predation of *Acanthaster planci*

The number of arms per starfish of six *A. planci* measured during this survey ranged from 15 to 16. Missing or regenerating arms are assumed to be the result of recent predation (Pearson & Endean, 1969). Fifty four out of 115, or 47%, of *A. planci* recorded during this survey had suffered recent predation and, in general, predation was more common (Fig. 4b) and more intense (Fig. 4c) on smaller starfish. For example, 78% of starfish less than 200 mm in diameter had one or more arms missing or regenerating, compared to 33% of starfish with diameters greater than or equal to 200 mm. Furthermore the predation intensity on starfish, measured as the mean number of arms missing or regenerating per starfish predated, was inversely correlated ($r=-0.67$, $0.005>p>0.002$) with mean starfish size. The overall mean number of arms missing or regenerating per starfish predated was 1.92 ($n = 54$). Predation also varied considerably between sites. For example, 25% of starfish ($n=19$) at Sailfish Reef had suffered recent predation in comparison to 64% ($n=33$) at Kendrew Island.

3.5 Live coral cover and community structure

Live coral cover on the seaward peripheral reefs ranged from 72.6% (transect 13.2) to 1.6% (transect 5.2), whereas at sites on the fringing reefs within the archipelago, live coral cover ranged from 17.6% (site 10) to 70.7% (site 11; Table 2). In general live coral cover decreased with increasing depth. For example mean live coral cover for seaward upper-reef slope sites (ie 1 to 9) was 25.5% and was significantly greater (Paired t-test; $t = 2.32$; $0.01<p\leq0.025$) than mean live coral cover at the same sites on mid-reef slope transects (mean=13.7%). A general westward trend of decreasing live coral cover occurred between sites on the peripheral reefs. Mean coral cover on the seaward reef transects for the eastern side of the archipelago, was significantly greater (mean=43.3%; Mann-Whitney U-test, $p\leq0.005$) than for the western side (mean = 11.1%). The low cover of live coral on Sailfish Reef is anomalous. This reef had a mean cover of about 4% which was considerably lower than comparable seaward reefs such as Hamersley Shoal (37%) and Kendrew Island (17%).

Benthic communities at the sites varied from reefs dominated by scleractinian corals (eg sites 2, 3, 11, 12 and 13), to reefs where soft corals (eg *Sarcophyton*) were either common (eg transects 5.1, 6.2) or dominant (eg transect 5.2), to reefs dominated by algae (eg transect 9.2). Other sites had more equal proportions of these community types (eg transects 1.1, 7.2; Table 5).

Seabed topography also varied considerably within and between sites. Upper reef slope transects were generally in the spur and groove zone (eg transects 5.1 and 8.1) where the seabed was extremely irregular. In contrast the topography of the mid-reef slope transects was more regular (eg transects 2.2 and 7.2; Table 5).

3.6 Recreational boating patterns

Over a five year period, 1421 boat sightings were made in the Dampier Archipelago and of these 1086 or 76% were in the western sector of the archipelago.

3.7 Seawater temperature

Seawater temperatures ranged from 23.7° - 24.7° C (Table 2).

4. DISCUSSION

The validity of conclusions from studies of animal populations is partly dependant on the the area of habitat surveyed and the number of animals observed. Underwater

Table 5: Community type, description and common attached benthic organisms recorded for each transect.

Transect	Community type	Hard coral 'health'	Transect description
1.1	coral/macroalae/ turf algae	healthy	Flat seabed with sparse coral cover and turf algae and macroalgae. *Acropora spp., Turbinaria spp., Sargassum spp., Halimeda spp., Caulerpa spp.*
1.2	coral/turf algae	healthy	Flat limestone platform. *Acropora spp., Pocillopora spp., Turbinaria spp.*
2.1	coral	healthy	Spur and groove zone, high cover of tabular and corymbose *Acropora spp. (A. hyacinthus, A. millepora, A. digitifera), Pocillopora spp.* also common.
2.2	coral	healthy	Flat reef with high cover of corals. *A. hyacinthus, A. millepora, Pocillopora spp.* Soft corals present. *Sarcophyton spp., Sinularia spp.*
3.1	coral	healthy	Spur and groove zone with high cover of tabular corals. *A. hyacinthus, A. millepora, A. digitifera, Pocillopora spp.*
3.2	coral/soft coral	healthy	High cover of live and dead tabular colonies. *A. hyacinthus, A. formosa, Turbinaria spp.* Soft corals present. *Sarcophyton spp.*
4.1	coral	unhealthy	Spur and groove zone. High cover of live and dead tabular colonies. Feeding scars common. *A. hyacinthus, A. formosa, Pocillopora spp.*
4.2	coral /turf algae	healthy	Rugged seabed. *Pocillopora damicornis* common.
5.1	coral/ soft coral	healthy	Spur and groove zone. *Pocillopora spp.* and *Sarcophyton spp.* common.
5.2	soft coral	healthy	Flat seabed with soft corals common. *Sarcophyton spp., Sinularia. spp.*
6.1	coral/turf algae/ zoanthids	healthy	Spur and groove zone. *A. millepora, Galaxea spp.* , zoanthids common. *(Polythoa sp.)*
6.2	soft coral	healthy	Very rugged seabed. Soft corals common. *(Sarcophyton spp., Sinularia spp.)*. Massive corals present. *Favites spp., Lobophyllia sp., Galaxea sp.*
7.1	coral/turf algae/ zoanthids	healthy	Irregular seabed with low coral cover. *Pocillopora spp., Porites spp.* zoanthids common. *(Polythoa sp.)*
7.2	coral/soft coral/ turf algae	healthy	Flat limestone pavement. *Acropora spp.,* small *Porites spp.* common. *Sarcophyton spp.* present.
8.1	coral	healthy	Spur and groove zone. High coral cover on top of spurs. *(A. hyacinthus, A. millepora, Pocillopora spp., Galaxea sp.)*
8.2	coral/soft coral	healthy	Very rugged reef interspersed with areas of sand. *Porites spp., Galaxea sp., Favites sp., Sarcophyton sp.*
9.1	coral	healthy	Spur and groove zone. High coral cover. *A. hyacinthus , Pocillopora spp.)*
9.2	turf algae/soft coral	healthy	Flat seabed. Soft corals common *(Sarcophyton sp., Sinularia sp.)*.
10.1	coral	healthy	Outer reef flat zone (inside *Porites* zone). Coral rubble and *Acropora spp.* present *(A. hyacinthus, A. formosa)*.
11.1	coral	healthy	High cover of arborescent and tabular corals. *(Acropora formosa, A. hyacinthus)*.
12.2	coral	healthy	Flat reef. High coral diversity. *A. hyacinthus, A. formosa, Pocillopora spp.,* small *Porites spp.*
13.2	coral	healthy	Reef dominated by large *Porites spp., Montipora spp.* and *A. hyacinthus* also common.

surveys of heterogeneously dispersed populations of diurnally cryptic organisms require intensive bottom searches. This inevitably limits the total area that can be surveyed in the time available and, as a result, the number of animals that can be observed. In this study a total of 115 starfish were recorded on twenty two 100 m x 10 m transects. Both the number of animals recorded and the area surveyed are relatively small and consequently the following discussion should be considered from this perspective.

Acanthaster planci abundance

The mean density of A. planci recorded at 13 sites in the Dampier Archipelago during October 1985 was 52 starfish per hectare. A. planci was not recorded at two sites within the archipelago and the mean starfish density of the 11 seaward reef sites was 58 per hectare, ranging from 170 at site 5 to 0 at sites 2 and 3. The mean density recorded by Wilson and Marsh (1974; 1975) on their study sites (excluding spot-check sites) at Kendrew Island, between October 1972 and May 1974, was about 67 starfish per hectare, ranging from a maximum of about 130 in October 1972 to a minimum of 26 in February 1974.

Comparisons with published estimates of natural densities at other locations suggest that A. planci densities in the Dampier Archipelago are 'normal' (Table 6); a conclusion also reached by Wilson and Marsh (1974; 1975). However, as Table 6 indicates, estimates of A. planci densities that constitute a 'normal population' vary by over three orders of magnitude and the definition of a 'normal population' varies considerably among researchers (eg Pearson and Endean, 1969; Chesher, 1970). A useful definition is given by Chesher (1970) who states that a normal population of A. planci is '... a concentration of A. planci whose combined predation pressure is balanced by the regrowth of coral'. This attempts to define a 'normal' population in terms of the carrying capacity of a particular reef by linking predation rates of A. planci to coral community parameters such as live coral cover, species composition and rates of coral growth and recovery.

These factors, however, vary markedly between reefs and thus densities of A. planci that constitute a 'normal' population on a particular reef will be a relative (ie site specific) rather than an 'absolute' number.

Table 6: Comparison of published densities of 'normal' populations of A. planci (from Potts, 1981) with A. planci densities recorded in the Dampier Archipelago during this survey.

Density (No. per ha)	Locality	Methods	References
0.06	Great Barrier Reef	Surface swims, tows and manta tows	Endean 1974; Endean and Stablum 1975
≤20	Red Sea	Bottom searches and manta tows	Ormond et al. 1973; Ormond and Campbell 1974
≤29	Panama	Bottom searches	Glynn et al. 1972; Glynn 1973
≤45	Gulf of California	Bottom searches	Dana and Wolfson 1970
>40	North-west Australia	Bottom searches	Wilson and Marsh 1975
<20-30	Micronesia	Surface swims and tows	Chesher 1969
50-100	Micronesia	Surface swims and tows	Dana et al. 1972 (from unpublished data of Chesher 1969)
52	Dampier Archipelago	Bottom searches	This study

For example, a 'normal' population of *A. planci* on a tropical reef may be 'abnormal' on a sub-tropical reef because of slower growth rates of corals on higher latitude reefs. Furthermore, if coral communities on an undisturbed reef having a 'normal' population of *A. planci* suffer catastrophic destruction (eg by cyclonic waves), and are prevented from recovering by pre-catastrophy densities of *A. planci*, then these densities, by definition, no longer constitute a 'normal' population.

Wilson and Marsh (1974; 1975) found aggregations of *A. planci* on their coral rich western sector study site at Kendrew Island in October 1972 and 1973 (means of 25 and 18 starfish per 1000 m^2 respectively) and suggested these were 'pre-spawning aggregations'. Apart from localised areas where mean densities were relatively high (12, 17 and 15 per 1000 m^2 at sites 4, 5 and 9 respectively), *A. planci* densities on other reefs in the Dampier Archipelago during October 1985, were generally low (ie 0-6 per 1000 m^2). These densities are comparable to the mean values ($\leq$ 6 starfish per 1000 m^2) that Wilson and Marsh (1975) found in their northern sector study site at Kendrew Island, and at times other than October in the western sector study site, and suggest that apart from very localised concentrations, there was no widespread aggregation of *A. planci* on the seaward reefs of the Dampier Archipelago during October 1985.

Acanthaster planci distribution

A. planci densities on reefs on the western side of the archipelago were an order of magnitude higher than on the eastern side. Live coral cover on the western reefs however, was significantly less than on the eastern side. Several reefs on the western side (ie sites 4, 5 and 9) had relatively high ($\geq$ 120 per ha.) densities of starfish and the coral community at one reef (site 4) appeared 'unhealthy' (ie visual patchiness of zooxanthellae in many of the coral colonies present). These results confirm initial qualitative assessments that *A. planci* abundance and live coral cover in the Dampier Archipelago appeared to be inversely related, and suggest that the low live coral cover on some reefs on the western side of the archipelago may be due to predation by *A. planci*.

No obvious reason exists for the apparent preference of *A. planci* for the western side of the archipelago. Coincidentally, recreational boating and presumably recreational fishing activities are also concentrated on this side of the archipelago. In other parts of the world the intensity of *A. planci* outbreaks have been linked to man's activities (eg Nishihira & Yamazato, 1974). Furthermore, the 'predator removal hypothesis', proposed by Endean (1969) and so termed by Potts (1981), invokes removal of *A. planci* predators by man as a cause of starfish outbreaks. More recently Endean (1977; 1982) has extended this hypothesis to include the effects of large territorial reef fish (eg *Promicrops lanceolatus*) which feed on juvenile *A. planci*. These type of fish are often a popular target of fishermen on coral reefs. From the limited data presented here no inferences can be drawn between man's activities in the Dampier Archipelago and the distribution of *A. planci*. It is interesting to note however, that anecdotal information suggests that *A. planci* is generally uncommon on Pilbara reefs, other than in the Dampier Archipelago. Thus again, but on a much larger spatial scale, *A. planci* appears to be common in the only area of tropical Western Australia where recreational boating activity is relatively high.

A possible explanation for the observed distribution of *A. planci* in the Dampier Archipelago, is that conditions on the reefs on the western side (around Kendrew Island and Sailfish Reef) favour recruitment of *A. planci* and these recruits then gradually disperse to other reefs. This would explain the higher densities of *A. planci* on the western side and the general eastward trend of increasing starfish size evident in our data (Table 3; Fig. 6).

Wilson and Marsh (1975) attempted to trace the movements of individual starfish in the Dampier Archipelago but were largely unsuccessful because of the difficulty of tagging *A. planci*. Of the twelve starfish that were individually recognisable after recovery (about 10 % of the total number tagged), nine had not moved more than about 50 m. Two starfish, however, had moved 300 m and 700 m in a south westerly direction between May and October 1973, and 1 had

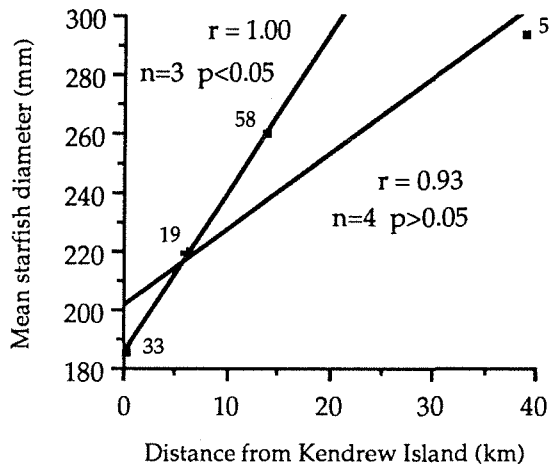moved 900 m in a north easterly direction between February and May 1974.

Figure 6. Mean size of *A. planci* for each reef in relation to the distance from Kendrew Island. Data points (from left to right) are Kendrew Island (sites 8 and 9), Sailfish Reef (sites 6 and 7), Nelson/Miller Rocks (sites 4 and 5) and Hamersley Shoal/Legendre Island (sites 1-3, 12 and 13). Numbers refer to sample sizes.

Although these longer movements are too few to determine trends, the data at least partly support the idea that starfish may disperse to other reefs in the archipelago. Elsewhere *A. planci* have been recorded to move up to 580 m in a week (Roads and Ormond, 1971) and there is indirect evidence that starfish are capable of moving large distances between reefs and over a variety of reef terrain (see Moran, 1986).

Starfish size is also related to diet (Lucas, 1984). Therefore starfish size differences may also reflect differences in the availability of food. However, although live coral cover is greater on the eastern side of the archipelago, live coral cover and mean starfish diameter on the western reefs (at sites 4 to 9) are not significantly correlated ($r=0.30$, $n=11$). Furthermore coral rich areas were close ($\sim$ 50 m) to the transects where most of the small starfish were recorded (eg transects 9.2, 5.2; Table 3). These data suggest that the eastward trend of increasing starfish size is not related to the availability of preferred food.

It is not known whether a similar trend occurs

in a south-westerly direction away from Kendrew Island and Sailfish Reef. However, the mean size of starfish ($n=64$) on these two reefs in April 1987 was about 240 mm, whereas 14 km to the southwest at Enderby Island (Fig. 1), the mean diameter of starfish ($n=48$) was 290 mm (Johnson and Stoddart, 1988). Again starfish size did not appear to be related to the availability of food with relative live coral cover being highest at Kendrew Island. These data at least provide further circumstantial evidence to support the admittedly tenuous ideas presented above of recruitment and dispersal of *A. planci* in the Dampier Archipelago.

The size frequency of *A. planci* recorded throughout the archipelago and the disproportionately high numbers of small starfish at Kendrew Island in October 1985, support the hypothesis that conditions on the western side of the archipelago favour recruitment of this starfish. If the bimodal distribution of starfish recorded in the present study does represent two successive year classes, then Kendrew Island appears to be the only site, of the reefs surveyed, where significant recruitment occurred in the summer of 1983/1984. This can be inferred from the high percentage (64 % of the total population) of 1.5-2 year old starfish on this reef in October 1985. Assuming spawning occurs during summer, then the reefs on the western side of the archipelago would provide a more sheltered habitat for *A. planci* for the first 6-8 months of their life due to winds in winter coming mainly from an easterly direction (Mills and Pitt, 1985).

A. planci was not observed at the two sites within the archipelago during this survey and have never been recorded on the inner reefs of the Dampier Archipelago south of the Malus Islands or on the *Acropora* dominated reefs adjacent to Angel Island, Gidley Island or Keast Island (Fig. 2). This may be partly related to the high seawater temperatures that occur on these reefs during summer. Between January and March, water temperatures in the Dampier Archipelago can exceed 30° C for several months, 31° C for several weeks (Woodside, 1985; Mills et al. 1986; Simpson, 1988) and have been recorded as high as 33.3° C (Simpson, unpublished data). Yamaguchi (1974) measured the rate of oxygen uptake of *A. planci* between 25-33°

14

C, and found uptake increased to 31° C, and then decreased sharply between 31-33° C. He estimated the incipient thermal death point of *A. planci* to be about 33° C. Lucas (1973) found that complete larval development could only occur between about 25-32° C. These studies suggest that high water temperatures on the inner reefs in the Dampier Archipelago during summer, will limit both larval development and survival of *A. planci*.

Wilson and Marsh (1975) suggested that the dispersal of the 'pre-spawning aggregations' of *A. planci*, observed at Kendrew Island in October 1972-1973, was possibly related to high sea temperatures. *A. planci* has also been observed *in situ* in the Dampier Archipelago, showing symptoms of thermal stress as described by Yamaguchi (1974). This occurred during periods when water temperatures were about 31° C (L M Marsh, pers. comm.). Thus high summer water temperatures possibly explain the absence of this starfish from inshore reefs and may also determine the seasonal distribution of *A. planci* on seaward reefs in the Dampier Archipelago.

Acanthaster planci size frequency distribution

Figure 4a indicates that the size frequency distribution of *A. planci* on the seaward reef slopes in the Dampier Archipelago, in October 1985, was bimodal. The mean diameter of the starfish < 200 mm in diameter was 158 mm and the mean of starfish ≥ 200 mm was 278 mm. This distribution may reflect different year classes or simply the different diet of starfish on these reefs. Lucas (1984) found that the growth rate of *A. planci* is dependant on diet and as such the size of a starfish is not necessarily related to its age. He urges caution when interpreting size frequency distributions of these animals. The fact that the size frequency distributions of starfish within these two 'year classes' closely resemble normal distributions (Fig. 4a), and that the difference between the mean values is approximately equal to the annual growth increment for *A. planci* within this size range (about 120 mm; Lucas, 1984), support the assertion that this bimodal distribution reflects successive year classes. Furthermore most of these smaller starfish occurred close

to reefs with extensive areas of live coral. This suggests that their size was not related to preferred food availability. If this distribution reflects successive cohorts, and if a summer spawning period is assumed (Wilson and Marsh, 1975), then the average age of these starfish would be 1.5-2 years and 2.5-3 years (Yamaguchi, 1974; Lucas, 1984). In comparison, the size frequency distributions of starfish at Kendrew Island in 1972 and 1973 were unimodal and had mean values of 314 mm and 280 mm respectively (Wilson and Marsh, 1975).

Acanthaster planci behaviour

Seventy six percent of starfish recorded during this survey were cryptic and this proportion is higher than the 57% recorded by Wilson and Marsh (1974) in October 1972. In the present study all starfish less than 200 mm in diameter were hidden, and this possibly explains the difference as Wilson and Marsh found few starfish in this size range. Predation was more common (Fig. 4b) and appeared more intense on smaller starfish (Fig. 4c). Remaining hidden during daylight, therefore, may be a strategy to avoid predators. The puffer fish *Arothron hispidus* has been reported to prey on *A. planci* in the Dampier Archipelago (Wilson et al. 1974) and although only two puffer fish were seen on the seaward reef sites, both were observed at Kendrew Island where the highest concentration of small starfish were found. Studies of predation of *A. planci* have shown that the proportion of starfish to have missing or regenerating arms ranges from 17% to 60% (see Moran, 1986). In this study 47% of starfish had suffered recent damage compared to 38% recorded by Wilson et al. (1974); again the difference was probably due to the higher proportion of smaller starfish recorded in the 1985 survey.

Thirty two starfish, or 28%, were observed feeding compared to between 30-50% reported by Wilson and Marsh (1974; 1975). The question of whether dispersed populations of *A. planci* feed nocturnally or diurnally remains unanswered as no consistent patterns have emerged from several studies (see Moran, 1986). In the present study the proportion of animals feeding during the day was generally low. An exception occurred at Nelson Rocks where most starfish in a small localised aggregation were actively feeding

(ie 70%). However, only 15% of starfish were feeding on the same day in another small aggregation at Miller Rocks, about 3 kilometres away.

A. planci were observed preying on hard corals and coralline algae. Acroporids, and in particular the table coral Acropora hyacinthus, were the most common prey of starfish during this study. These observations are consistent with the findings of other studies that indicate that branching and tabulate Acropora appear to be the preferred diet of A. planci (see Moran, 1986).

Coral community structure

Two hundred and sixteen species of scleractinian coral from 57 genera have been recorded in the Dampier Archipelago (Veron and Marsh, 1988). Corals occur on extensive reefs along the periphery of the archipelago and on small patch and fringing reefs next to islands and rocky outcrops. The high diversity of corals is due to the wide range of habitats available (Marsh, 1978). These range from exposed offshore reefs where currents are strong and water clarity is high, to protected inshore reefs where turbid water, low current speeds and high sediment deposition rates are common (Simpson, 1987; 1988).

Coral abundance and species composition vary markedly along this environmental gradient. For example, the extensive reef at Hamersley Shoal (Fig. 2) is dominated by the genus Acropora, and in particular by the tabular acroporid, Acropora hyacinthus. Pocilloporids such as P. damicornis and P. eydouxi are also common on these reefs whereas favids and other scleractinian genera are poorly represented (Simpson, 1988). In comparison, the small patch reefs near Dampier (Fig. 2) consist of silt tolerant species including Porites, Turbinaria, favids and occasional stunted Acropora colonies. Generic diversity is low in both of these habitats (see Marsh, 1978).

Higher generic diversity occurs on the fringing and patch reefs in the central eastern areas of Mermaid Sound (see Marsh, 1978). This may be because the greater seasonal variation in hydrological conditions on these reefs favour the clear water and silt tolerant assemblages at different times of the year.

During winter, conditions are similar to the offshore reefs with periodic exposure to swell waves and high water clarity. In summer, conditions are similar to inshore reefs, with turbid water and high sediment loads (Simpson, 1985; 1987; 1988). In addition, the more fragile species such as the arborescent and tabular acroporids are periodically devastated by cyclonic wave action (personal observations by CJS). Thus during summer, conditions on these reefs are sub-optimal for the fast growing, clear water Acropora species that dominate the offshore coral communities (Simpson, 1985; 1988). This reduces their competitive advantage which allows silt tolerant and slower growing species to co-exist.

Live coral cover and Acanthaster planci abundance

Mean A. planci density on the seaward reefs on the western side of the Dampier Archipelago was an order of magnitude higher than on the eastern side. In contrast, mean live coral cover on the seaward reefs was about 4 x higher on the eastern side of the archipelago. Apart from this broad relationship, a statistically significant correlation does not occur between A. planci densities and live coral cover in the Dampier Archipelago. This is hardly surprising given the markedly different temporal scales of the processes involved ie A. planci predation and coral regrowth.

The unusually low cover of live coral on Sailfish Reef is anomalous (Table 2; Fig. 2). Prior to 1975, extensive coral communities flourished on this reef (L M Marsh, pers. comm.). During 1972-1974, reefs on the western side of Kendrew Island, at the south-western end of Sailfish Reef, were extensively damaged by A. planci, (Wilson and Marsh, 1974; 1975). Marsh (1978) attributes the decline of the coral communities on Sailfish Reef to the effects of this 'outbreak' and to cyclonic wave damage that occurred in February, 1975.

In contrast, coral communities at Hamersley Shoal, which has a similar orientation to Sailfish Reef in relation to exposure to cyclonic waves (Fig. 2), has a high cover of live coral. During this survey, live coral cover on parts of the upper reef front exceeded 60 % (Table 2), and has been recorded as high

as 78% (Simpson, 1988). If the coral communities on this reef suffered similar catastrophic destruction (to Sailfish Reef) by cyclonic waves during February 1975, then recovery has been rapid. This raises the question of why coral communities on Sailfish Reef have not similarly recovered. Interestingly coral communities at nearby Kendrew Island appear to have recovered reasonably well, with extensive live coral cover occurring on parts of this reef, particularly on the tops of the spurs (eg transects 8.1 and 9.1; Table 2).

The difference in live coral cover on these reefs is unlikely to be the result of differential coral recruitment as Kendrew Island and Sailfish Reef are only a few kilometres apart. Although larval settlement and therefore recruitment, may vary markedly on adjacent reefs from year to year, net differences averaged over longer time periods (ie 10 years) are likely to be less. An alternative hypothesis is that because the combined events of February 1975 reduced live coral cover on Sailfish Reef to below a 'critical' level, A. planci predation was necessarily focussed on the corals remaining and on any juvenile corals that subsequently recruited onto this reef. As a result, significant regrowth of corals on this reef, over the 10 years to 1985, was prevented.

Live coral cover and A. planci densities recorded on Sailfish Reef, together with published predation rates, support this hypothesis. For example if mean feeding rates per starfish in the Dampier Archipelago are similar to published values of approximately 6 m² of live coral per year (Moran, 1986), then the mean densities of A. planci recorded at Sailfish Reef in October 1985 (~ 50 per ha.) were sufficient (assuming all were coral feeders) to destroy about 3 % or 300 m² of live coral per hectare every year. This represents a significant proportion (~70 %) of the standing crop of live coral on this reef. In contrast, sufficient live corals existed on the reefs at Kendrew Island in October 1985, to enable coral cover to increase despite greater densities of A. planci (ie the carrying capacity of this reef was not exceeded).

The carrying capacity of a reef can be determined by dividing the annual areal increase in live coral by the mean annual predation rate per starfish. Increase in live coral cover can be estimated by knowing the size frequency distribution, percentage cover and growth rates of the dominant coral species. For example the reef at transect 9.1 consists mainly of the tabular coral, *Acropora hyacinthus*, and live coral cover in October 1985 was about 30%. Forty four colonies of *Acropora hyacinthus* were selected randomly at this site and their diameters measured (Fig. 7).
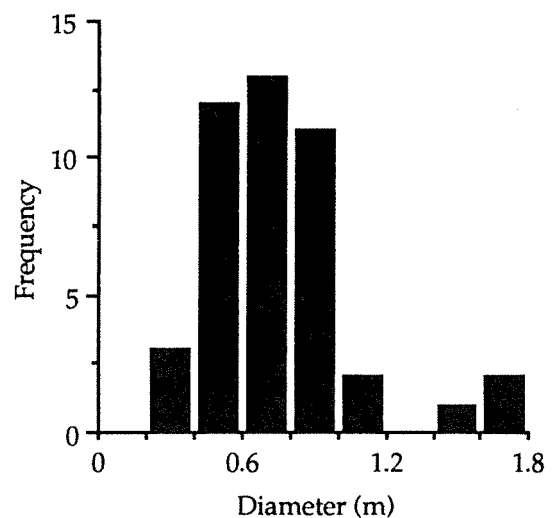

Figure 7. Size frequency distribution of 44 colonies of *Acropora hyacinthus* near transect 9.1.

The total projected area of these colonies was 21.6 m² (assuming circular colonies). This species extends its branches radially by about 120 mm per year on seaward reefs in the Dampier Archipelago (Simpson, 1988). At an annual growth rate of 120 mm per year, the 44 colonies would increase their total projected area by 61%, to 34.8 m². Thus live coral cover on this reef would increase from 30% to 48%; that is an additional 1800 m² of live coral per ha. would be produced on this reef in one year. This is equivalent to the annual predation of about 300 starfish. Thus the carrying capacity of this reef in October 1985 was about 300 starfish per hectare.

The density of starfish on this reef was about 50 per hectare; well below the carrying capacity at the time of this survey. As a result live coral cover would have increased despite predation by A. planci. It is likely the calculated carrying capacity is overestimated as a result of the assumptions

made concerning coral community parameters such as species composition and colony size frequency distribution. However, the carrying capacities of this reef and Sailfish Reef, in October 1985, were obviously very different and may explain the differences in live coral cover. Interestingly, the densities of *A. planci* that caused the devastation of corals on the reef at Kendrew Island, in 1972 and 1973, were 250 and 180 starfish per hectare respectively (Wilson and Marsh, 1975). These densities are considerably closer to the calculated carrying capacity of this reef in October 1985.

Comparisons of *A. planci* densities, predation patterns, and the size frequency distribution of live corals on comparable (in relation to other destructive agents such as cyclonic waves) reefs in the Dampier Archipelago, provide additional evidence to support the hypothesis that recovery of corals on Sailfish Reef is prevented by *A. planci* predation. *A. planci* was observed feeding on 4 genera of corals at Sailfish Reef and most of these colonies were less than 0.05 m in diameter. Furthemore the mean size of live coral colonies recorded at Sailfish Reef was 0.20 m and was significantly less ($t = -3.062$, $p \leq 0.005$) than the mean of 0.50 m at Kendrew Island. In contrast, mean colony size at Hamersley Shoal, where the mean *A. planci* density was less than 0.2 starfish per 1000 m², was 0.95 m. This was significantly greater than mean colony size at Kendrew Island ($t = 3.816$, $p \leq 0.0005$) and Sailfish Reef ($t = 5.245$, $p \leq 0.0005$). In addition, the size frequency distribution of coral colonies at Sailfish Reef (Fig. 8a) is more positively skewed, with a higher proportion of small colonies and fewer colonies exceeding 1 m, compared to the coral communities at Kendrew Island (Fig. 8b) and particularly at Hamersley Shoal (Fig. 8d). These observations suggest that, because of the low cover of live corals on Sailfish Reef, *A. planci* predation is focussed necessarily on any juvenile corals that recruit onto this reef.

Observations of *A. planci* feeding habits provide further evidence to support this hypothesis. Thirty two starfish were recorded feeding (Table 4), 27 on hard corals and 5 (or 15 %) on coralline algae (Fig. 6). The mean size of *A. planci* feeding on corals was ~290 mm ($n=27$).
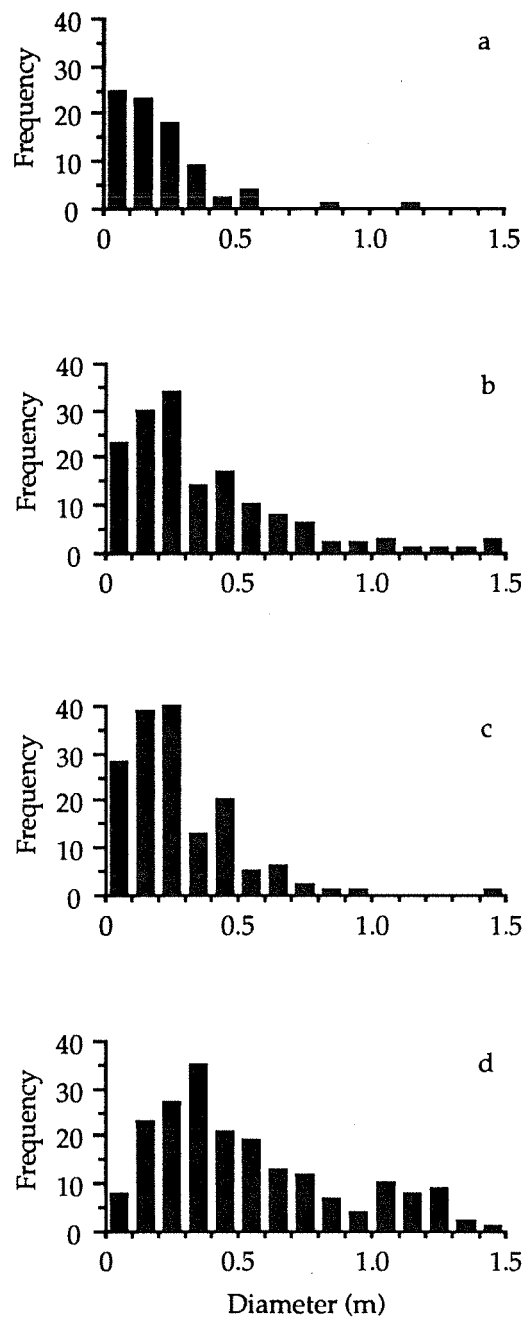

Figure 8. Size frequency of live coral patches on four reef types in the Dampier Archipelago: (a) Sailfish Reef (sites 6 and 7); (b) Kendrew Island (sites 8 and 9); (c) Nelson/Miller Rocks (sites 4 and 5); (d) Hamersley Shoal (sites 1, 2 and 3). Live coral patches > 1.5 m were included in the determination of mean patch size but were not included in this diagram and were : (a) 0; (b) 7; (c) 3 and (d) 35.

Only one starfish less than 200 mm in diameter was observed feeding on corals.

This represents less than 3% of the total number of starfish within this size range. In contrast 33% of starfish with diameters greater than 200 mm were feeding on hard corals. These data indicate that, in general, the smaller starfish (ie < 200 mm diameter) were not feeding on hard corals at the time of this survey. Whether these 'instantaneous' observations are indicative of long-term feeding patterns of A. planci in the Dampier Archipelago is unknown.

Because of their cryptic habit, the feeding behaviour of the smaller starfish could not be determined easily by visual examination. Most of these starfish were found in areas of low coral cover, even though extensive hard coral communities usually occurred within 100 m. This suggests that other known A. planci foods, such as coralline or epilithic algae, may have been preferable. This conclusion is inconsistent with the findings of Lucas (1984) who considered A. planci in the size range 10-200 mm to be coral-feeding juveniles with high feeding and high growth rates. The apparent preference for algal dominated, deeper-water habitats by starfish less than 200 mm in diameter, may also be a strategy to avoid predators. Predation was more common and more intense on starfish within this size range (Figs 4b and 4c) and this may partly explain why all of these smaller starfish displayed a cryptic habit. In contrast, 66% starfish with diameters of 200 mm or greater were hidden.

If starfish smaller than about 200 mm do not generally prey on hard corals in the Dampier Archipelago, then a reef with a higher proportion of these smaller starfish will incur less damage. At Kendrew Island and Sailfish Reef the proportion of these smaller starfish was 70% (n=33) and 27% (n=19) respectively. Thus, although the overall densities of A. planci on Kendrew Island reefs are 1.7 times higher than on Sailfish Reef, the density of 'coral-eating' starfish (ie >200 mm) is considerably lower (ie about 2/3). These data provide further evidence to support the hypothesis that coral communities at Sailfish Reef are prevented from recovering as a result of predation by A. planci.

Live coral cover on the upper reef slope at Nelson Rocks (ie site 4.1) decreased from approximately 65% in August 1983 to about

24% in October 1985. Although live coral cover at this site was estimated visually in 1983, the relationship between estimated and measured live coral cover in Figure 9 suggests this estimate should be within 10%.
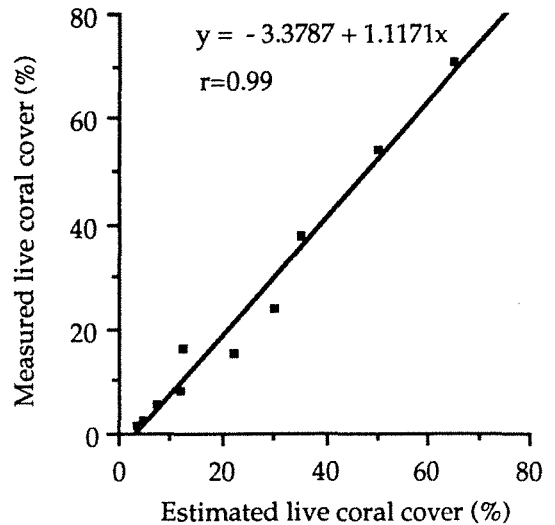

$$y = -3.3787 + 1.1171x$$
$$r=0.99$$

Figure 9. Correlation between live coral cover measured by line transect and by visual estimate.

The results of the preliminary survey and timed swim counts in 1983, and the survey in 1985, suggest that parts of this reef had relatively high densities (for the Dampier Archipelago) of A. planci for the two years prior to 1985. The marked reduction in live coral at this site therefore appears to be the result of A. planci predation. The unusually high proportion of starfish that were actively feeding during the day at this site in 1985, and the size frequency distribution of coral colonies in this area (Fig. 8c), support this conclusion. The size frequency distribution of corals on this reef is similar to the 'recovering' community at Kendrew Island (Fig. 8b), but quite different to the 'devastated' community at Sailfish Reef (Fig. 8a) and the 'pristine' community at Hamersley Shoal (Fig. 8d).

Distribution of A. planci on Western Australia coral reefs.

In general A. planci appears to be rare on Western Australian coral reefs other than the reefs off the Pilbara coast, that is between latitudes 17°-22° S. This distribution may be related to the sea temperatures that prevail on these reefs during the assumed summer

spawning season. For example, mean monthly seawater temperatures on the northern Ningaloo Reef (latitude 22° S) between November and January, the assumed spawning season of A. planci in Western Australia (Wilson and Marsh, 1975), range between about 23.5-25.5° C (Pearce, 1986; Simpson, 1988). If A. planci spawns on Ningaloo Reef during this period, then the temperature regime will be unfavourable for the survival of large numbers of larvae.

Lucas (1973) found that A. planci larvae exposed to continual temperatures of 24-25° C did not develop beyond the early brachiolaria stage and suggested that complete larval development occurs between the temperature range of 25-32° C. Furthermore he noted that development and survival of A. planci larvae was highest between 28-32° C. In the Dampier Archipelago, mean temperatures, between November and January, range from about 27-30° C (Simpson, 1988), that is mostly within the optimum temperature range for development and survival of A. planci larvae. This possibly explains why A. planci is relatively common on these reefs. Conversely, sub-optimal temperatures may explain the apparent low densities of A. planci on the Ningaloo Reef by limiting larval development and therefore settlement. The limited data on the size of A. planci observed on Ningaloo Reef, provide some evidence to support this hypothesis, and suggest that recruitment may be restricted to immigration of starfish from populations further north. In general the few A. planci that have been observed on this reef have been large individuals up to about 600 mm in diameter (M. Forde, pers. comm.). Starfish over 350 mm in diameter are considered by Lucas (1984) to be senile adults with low fecundity. Recruitment of A. planci onto Ningaloo Reef, as a result of southward dispersal of larvae from breeding populations further north, is also unlikely due to unfavourable water circulation patterns at this time of year. Winds are usually from the southwest during November to January (Hearn et al. 1986), probably resulting in a net northerly drift of surface waters.

Coral reefs in Western Australia north of about latitude 17° S, that is off the Kimberly coast (Fig. 1), are mainly fringing and patch reefs next to islands and rocky outcrops (Hatcher et al. 1987). Because of the high tidal amplitude (in some areas over 10 m) of this coastline, water clarity is usually poor and high levels of suspended material are common. As a result coral reefs in this area occur mainly in relatively shallow depths and most are intertidal. Water temperatures on these reefs in summer are likely to be similar to, or more extreme than, inshore reefs in the Dampier Archipelago (see Pearce, 1986). If so, conditions on many of these reefs are likely to be sub-optimal for larval development and survival of A. planci and this may explain the apparent low densities of starfish in the region.

The reefs of the Kimberly coast and Ningaloo Reef have not been surveyed specifically for A. planci. However, faunal surveys have been conducted in both areas by the Western Australian Museum and only occasional sightings of A. planci have been made (L M Marsh, C Bryce, pers. comm.). Furthermore we have dived extensively on the Ningaloo Reef and have never observed A. planci. These observations suggest that the assumed low densities of A. planci on these reefs are likely to be confirmed if, and when, A. planci surveys are conducted. From the preceding discussion, the distribution of A. planci on Western Australian coral reefs may be related to the sub-optimal conditions that occur during the assumed breeding season on reefs outside latitudes 17-22° S. It is interesting to note that this distribution closely parallels the distribution of A. planci on the Great Barrier Reef (Potts, 1981; Moran, 1986).

5. CONCLUSIONS

Although A. planci was relatively common on seaward reefs in the Dampier Archipelago, it was not recorded at the two inshore reef sites. The mean density of A. planci was 52 starfish per hectare over the surveyed area. This is within the density range for 'normal populations' of A. planci on coral reefs worldwide. Starfish distribution on these reefs, however, was extremely variable with mean site densities ranging from 0 to 170 starfish per hectare.

A. planci densities on the seaward reefs of the western side of the archipelago were an

order of magnitude higher than on reefs in the eastern side. Conversely live coral cover was about four times higher in the eastern half of the archipelago. The size frequency distribution of the starfish population was bimodal with two apparent 'year classes'; 1+ and 2+. The average age of the 1+ year class was about 1.5-2 years old, and most of these smaller starfish occurred on reefs in the far western side of the archipelago. The assumed mean age of these 1+ starfish suggests that they recruited onto these reefs in the summer of 1983/1984. A trend of increasing size of A. planci, from west to east, is evident. This may be the result of conditions on the western side of the archipelago being more favourable for A. planci recruitment and the subsequent dispersal of these recruits or, alternatively it may be related to diet.

A. planci were not observed on two reefs within the archipelago and have not been observed by the authors on any inner or protected reefs. High summer sea temperatures on these reefs are likely to restrict the distribution of A. planci in the Dampier Archipelago to the seaward reefs and to some of the reefs of the outer islands, such as Goodwyn Island.

Extensive reefs occur on the seaward periphery of the archipelago and are dominated by acroporid, and to a lesser extent, pocilloporid species. The tabular coral Acropora hyacinthus is particularly dominant on these reefs. Live coral cover is significantly higher in the eastern half of the archipelago and on upper seaward reef slopes. Some parts of these reefs had a live coral cover of over 70%. In contrast, live coral cover on reefs in the western side of the archipelago ranged from about 2-30%. The low cover of coral on Sailfish Reef (~4%) is anomalous. It is postulated that persistent predation of juvenile corals by a small population of A. planci on Sailfish Reef is responsible for the slow recovery of this reef since 1975. During the 1985 survey, a small aggregation of A. planci were causing considerable damage to the reef at Nelson Rocks and A. planci predation appears to be responsible for the marked decrease in live coral cover that occurred at that reef between 1983-1985.

Observations suggest that, apart from the reefs off the Pilbara coast, A. planci is rare on Western Australian coral reefs. South of latitude 22° S, sub-optimal temperatures during the assumed breeding season of A. planci may inhibit larval development and unfavourable current patterns may limit southward dispersal of larvae from breeding populations on more northern reefs. Thus recruitment of A. planci onto Ningaloo Reef may be limited to immigration of individuals from populations further north and may explain the apparent low densities of starfish on this reef. Conversely, supra-optimal temperatures on the predominantly shallow, intertidal coral reefs off the Kimberly coast (north of latitude 17° S) during summer, may inhibit larval development and restrict the summer distribution of A. planci to the less extensive sub-tidal reefs that occur in this region, thereby keeping population numbers low.

6. ACKNOWLEDGEMENTS

7. REFERENCES

Barnes J & Endean R (1964). A dangerous starfish- *Acanthaster planci* (Linne). *Medical Journal of Australia* 1: 592-593.

Chesher R H (1969). Destruction of Pacific corals by the seastar *Acanthaster planci*. *Science* 165: 280-283.

Chesher R H (1970). *Acanthaster*: a disaster? *Science* 167: 1275.

Dana T & Wolfsen A (1970). Eastern Pacific crown-of-thorns starfish populations in the lower Gulf of California. *Trans. of the San Diego Society of Natural History.* 16: 83-90.

Dana T F, Newman W A & Fager E W (1972). *Acanthaster* aggregations: Interpreted as primarily responses to natural phenomena. *Pacific Science* 26 (4): 355-372.

Endean R (1969). Report on investigations made into aspects of the current *Acanthaster planci* (crown of thorns) infestations of certain reefs of the Great Barrier Reef. Fisheries Branch, Queensland Department of Primary Industry. Brisbane. 35 pp.

Endean R (1974). *Acanthaster planci* on the Great Barrier Reef. *Proceedings of the Second International Coral reef Symposium.* I. (Great Barrier Reef Committee, Brisbane). 563-576.

Endean R (1977). *Acanthaster planci* infestations of reefs of the Great Barrier Reef. *Proceedings of the ThirdInternational Coral reef Symposium.* I. (Manila, Philippines). 185-191.

Endean R (1982). Crown-of-thorns starfish on the Great Barrier reef. *Endeavour.* 6: 10-14.

Endean R & Stablum W (1975). Population explosions of *Acanthaster planci* and associated destruction of the hard coral cover of reefs of the Great Barrier Reef, Australia. *Environmental Conservation* 2: 247-256.

Glynn P A, Stewart R H & McCosker J E (1972). Pacific coral reefs of Panama: structure, distribution and predators. *Geol. Rundsch.* 61: 483-519.

Glynn P A (1973). *Acanthaster*: effect on coral reef growth in Panama. *Science* 180: 504-506.

Hatcher B G, Allen G R, Berry P F, Hutchins B J, Marsh L M, Simpson C J & Slack-Smith S M (1987). Australia (Western). Pp 1-53 in: Wells S M (ed). *IUCN Directory of Coral Reefs of International Importance.* Vol 2. (Conservation Monitoring Centre, Cambridge, UK).

Hearn C J, Hatcher B G, Masini R J & Simpson C J (1986). Oceanographic processes on the Ningaloo Coral Reef, Western Australia. (Centre for Water Research, University of Western Australia). Report No. ED-86-171. 79pp.

Henderson J A and Lucas J S (1971). Larval development and metamorphosis of *Acanthaster planci* (Asteroidea). *Nature* 232: 655-657.

Johnson D B and Stoddart J A (1988). Report on surveys of the distribution, abundance and impact of *Acanthaster planci* on reefs within the Dampier Archipelago (Western Australia): April 1987. (Australian Institute of Marine Science, Townsville). 15 pp.

Loya Y (1978). Plotless and transect methods. Pp 197-217 in: Stoddart D R & Johannes R E (eds). *Coral Reefs: research methods.* (Monographs on Oceanographic Methodology No 5, UNESCO, Paris). 581 pp.

Lucas J S (1973). Reproductive and larval biology of *Acanthaster planci* (L.) in Great Barrier Reef waters. *Micronesia* 9:197-203.

Lucas J S (1984). Growth, maturation and effects of diet in *Acanthaster planci* (L.) (Asteroidea) and hybrids reared in the laboratory. *Journal of Experimental Marine Biology and Ecology,* 79 : 129-147

Marsh L M (1978). Report on the corals and some associated invertebrates of the Dampier Archipelago. In: *Report on the marine fauna and flora of the Dampier Archipelago.* (Unpublished report, Western Australian Museum). 66 pp.

Marsh L M (1986). Part VI: Echinoderms. Pp 63-74 in: P F Berry (ed). *Faunal Surveys of the Rowley Shoals, Scott Reef and Seringapatam Reef, North-western Australia.* (Records of the Western Australian Museum). Supplement No 25. 106 pp.

Mills D A & Pitt D R (1985). Summary of anemometer data from Conzinc Island: September 1981 to July 1984. (Western Australian Department of Conservation and Environment, Perth). Environmental Note 176: 6 pp.

Mills D A, Pitt D R & Simpson C J (1986). Summary of current meter data from the Dampier Archipelago: 1981-1984. (Western Australian Department of Conservation and Environment, Perth). Environmental Note 178: 11 pp.

Moran P J (1986). The *Acanthaster* phenomenon. *Oceanography and Marine Biology Annual Review* 24: 379-480.

Nishihira M & Yamazato K (1974). Human interference with the coral reef community and *Acanthaster* infestation of Okinawa. *Proceedings of the Second International Coral Reef Symposium.* I. (Great Barrier Reef Committee, Brisbane). 577-590.

Ormond R F G & Campbell A C (1974). Formation and breakdown of *Acanthaster planci* aggregations in the Red Sea. *Proceedings of the Second International Coral reef Symposium.* I. (Great Barrier Reef Committee, Brisbane). 595-619.

Ormond R F G, Campbell A C, Head S H, Moore R J, Rainbow P R & Saunders A P (1973). Formation and breakdown of aggregations of the crown-of-thorns starfish, *Acanthaster planci* (L). *Nature* 246: 167-169.

Pearce A F (1986). Sea temperatures off Western Australia. *Fishing Industry News Service.*19 (2): 6-9.

Pearson R G & Endean R (1969). A preliminary study of the coral predator *Acanthaster planci* (L) (Asteroidea) on the Great Barrier Reef. *Fisheries Notes of Department of Harbours and Marine, Queensland* 3: 27-55.

Potts D C (1981). Crown-of-thorns starfish-man induced pest or natural phenomenon? Pp 55-86 in: Kitching R L & Jones R E (eds). *The ecology of pests: some Australian case histories.* CSIRO (Australia).

Roads C H and Ormond R F G (1971). New studies on the coral predating crown-of-thorns starfish. A research project in the Red Sea. 124pp. Privately published report.

Simpson C J (1985). Environmental factors affecting coral growth in the Dampier Archipelago, Western Australia. (Environmental Protection Authority, Perth). Environmental Note 168. 14pp.

Simpson C J (1987). Growth, metabolism and reproduction of corals in northwestern Australia. PhD Thesis, University of Western Australia. 238pp.

Simpson C J (1988). Ecology of scleractinian corals in the Dampier Archipelago, Western Australia. (Environmental Protection Authority, Perth) Technical Series No 23. 238pp.

Veron J E N & Marsh L M (1988). Hermatypic corals of Western Australia: records and annotated species lists. (Records of the Western Australian Museum, Perth). Supplement No 29. 136 pp.

Wilson B R & Marsh L M (1974). *Acanthaster* studies on a Western Australian coral reef. *Proceedings of the Second International Coral Reef Symposium.* I. (Great Barrier Reef Committee, Brisbane). 621-630 pp.

Wilson B R & Marsh L M (1975). Seasonal behaviour of a "normal" population of *Acanthaster* in Western Australia. Pp 167-169 in: *Proceedings of the crown-of-thorns seminar. Brisbane, 6 September, 1974.* (Australian Government Publishing Service, Canberra).

Wilson B R, Marsh L M & Hutchins B (1974). A puffer fish predator of crown-of-thorns in Australia. *Search* 6: 601-602.

Wilson B R & Stoddart J A (1987). A thorny problem. Crown of thorns starfish in WA. Pp 35-39 in: *Landscope* (Department of Conservation and Land Management, Perth). 55pp.

Woodside Offshore Petroleum Pty. Ltd (1985). Annual report on meteorological and oceanographic measurements, Mermaid Sound and North Rankin area, 1984. (Woodside Offshore Petroleum Pty. Ltd). Document No. A9610RT004.

Yamaguchi M (1974). Growth of Juvenile *Acanthaster planci* (L.) in the laboratory. *Pacific Science* **28**: 123-38..

Zann L (1987). The controversy: natural cycle or not? Pp 17-19 in: Zann L & Eager E (eds). *The crown of thorns starfish.* (Australian Science Magazine, Issue No 3. Darling Downs Institute Press, Toowoomba). 55 pp.

Zann L & Eager E (1987) (eds). The crown of thorns starfish. *Australian Science Magazine,* Issue No 3. (Darling Downs Institute Press, Toowoomba). 55 pp.