Fine-scale surveys of crown-of-thorns starfish *Acanthaster planci* in the Cairns Section of the Great Barrier Reef Marine Park. Status report 2000-01.

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Reefwatch Australia

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EXECUTIVE SUMMARY

In 2000-01, intensive transect-based surveys of crown-of-thorns starfish (*Acanthaster planci*) and associated live hard coral cover were conducted on 9 mid-shelf reefs all located in the Cairns Section of the Great Barrier Reef Marine Park.

We recorded a total of 398 *A. planci* on the 9 reefs surveyed. Juvenile starfish (est. age 1) accounted for 200 (50.3%) of these with a further 69 (17.3%) individual sub-adults (est. age 2) and 129 (32.4%) adult (est. age 3) starfish recorded in the 300 benthic transects sampled.

Adult *A. planci* (est. age 3 and older): Densities of adult starfish across individual survey reefs ranged from 0.0±0.0 (reef mean ± 1 S.E.) individuals per 250 m^2 recorded on 2 reefs (14-132b and 16-024) to 2.95±0.79 individuals at Thetford Reef (16-068) - approximately 4-times above what is considered to be a sustainable density – leading to its classification as an Active Spot Outbreak (ASO).

Sub-adult *A. planci* (est. age 2): Densities of sub-adult starfish on individual survey reefs ranged from 0.0±0.0 (reef mean ± 1 S.E.) individuals per 250 m^2 recorded at Unnamed Reef (16-024) up to 0.43±0.14 individuals recorded at Irene Reef (15-084). We detected no new Incipient Spot Outbreaks (ISO) during the 2000-01 survey season.

Juvenile *A. planci* (est. age 1): Densities of juvenile starfish across individual survey reefs ranged from 0.05±0.03 (reef mean ± 1 S.E.) individuals per 250 m^2 at Thetford Reef (16-068) to 2.25±0.39 individuals recorded at Irene Reef (15-084). Juvenile starfish densities observed across the nine survey reefs in 2000-01 are unlikely to be developing into renewed outbreaks in the near future.

All nine core reefs surveyed annually since 1994-95 have experienced active spot and/or reef-wide COTS outbreaks over the past 7 years. Generally, these outbreaks have been severe with starfish feeding activity resulting in average, reef-wide losses of hard coral cover ranging from approximately 66% (at Unnamed Reef 15-070) to 89% (at Rocky Islets Reef b) of the initial live coral cover present prior to the outbreaks. Remnant live hard coral cover averaged across these reefs now ranges from a very low 5% live cover to a maximum of around 10-15% cover.

Outbreaking populations of *A. planci* across the nine core reefs have been characterised by the presence of multiple cohorts or year classes with size-frequency distributions of starfish indicating that between four and seven consecutive year classes ('pseudo-cohorts') were combining to cause the severe recent outbreaks in this region.

The observed pattern of starfish recruitment also suggests that COTS outbreaks, at least in this part of the Great Barrier Reef, are not the result of a single unusual event that causes a once off, yet highly successful recruitment pulse. Rather, it would appear that the observed outbreaks are the result of relatively persistent environmental factors and conditions favouring *A. planci's* recruitment success synchronously across a geographic area spanning several degrees of latitude.

The strong 1997-98 cohort of *A. planci*, first observed during the 1998-99 surveys season, has had varied impacts across the set of nine core reefs. In 1999-00, all nine reefs supported significant densities of sub-adult starfish leading to local classifications of renewed Incipient Outbreaks (IO). However, in all but one case, it appears that remnant coral cover of only 5-10%, as recently recorded on these reefs, was insufficient to allow for further growth and maturation of this cohort. The only survey reef seriously affected by the 1997-98 cohort was Thetford Reef (16-068) where the available hard coral cover was recorded at around 15% live cover – apparently a sufficiently large source of suitable prey items to allow for starfish maturation and the development of a renewed outbreak.

Whilst the 1997-98 cohort of starfish has largely failed to reach maturity, there are indications that it may have had a significant effect on the onset and magnitude of the recovery process on COTS-affected reefs. Personal observations made in recent years suggest a strong preference by small juvenile COTS for feeding on recently recruited hard corals. It appears highly likely that the observed feeding preferences have resulted in significant losses to local coral populations dominated by small remnant as well as newly settled corals.

Based on our observations over the past 7 years, we suggest that the key to understanding the ultimate cause(s) of the observed outbreaks lies in the continuation of dedicated fine-scale monitoring of COTS with the aim of further investigating the dynamics of *A. planci's* populations in this critically important area of the GBR Marine Park. With regard to the need for ongoing monitoring, the period between successive outbreak episodes may be of particular

importance. At this stage, our understanding of the population structure and dynamics of *A. planci* during the inter-outbreak period is virtually non-existent. Detailed records on starfish abundance and size-frequency distributions within local and regional populations appear to offer the only realistic chance of improving our understanding of this critically important phenomenon.

Intensive fine-scale monitoring of *A. planci* and associated live hard coral cover should be continued to maximise the chances of (a) detecting the early signs of renewed COTS activity, (b) identifying possible signs of further reef degradation and reduced coral recovery rates and (c) improving our understanding of outbreak causality.

As outbreaks of COTS have been shown to be the single-most important source of coral mortality in the Great Barrier Reef World Heritage Area, those responsible for the continued and sustainable management of this critical area should feel obliged to intensify their efforts at trying to more fully understand the relative importance of natural versus human factors in the ultimate causation of the outbreak phenomenon.

1. INTRODUCTION

1.1 Background

Twice in the last 40 years, major outbreaks of the crown-of-thorns starfish (*Acanthaster planci)* on the Great Barrier Reef (GBR) have apparently originated on reefs in the Cairns Section ($14^{o}30'S$ - $17^{o}52'S$) of the Great Barrier Reef Marine Park (GBRMP) (Kenchington 1977, Moran *et al.* 1992). During the first two outbreak episodes in the 1960's and again in the 1980's, outbreaking populations of *A. planci* were first observed on Green Island Reef off Cairns ($16^{o}46'S$) with a number of surrounding reefs also being affected at about the same time (Moran 1986). However, dedicated surveys of starfish populations were initiated only several years later, when the outbreaks had apparently progressed several hundreds of kilometres from their suggested geographic origin (Dight *et al.* 1990, Moran *et al.* 1992).

Despite a considerable research effort, particularly from the mid-1980's to the mid-1990's, the ultimate cause(s) of *A. planci* outbreaks on the GBR and elsewhere remain unknown (see review by Engelhardt and Lassig 1997). It is generally accepted that a lack of reliable data on the dynamics and age structures of *A. planci* populations before, during and after outbreaks is one of the main reasons for the apparent failure of this research effort to more fully understand outbreak causality (Birkeland and Lucas 1990, Engelhardt and Lassig 1997).

Surveys of *A. planci* populations on the GBR and in other parts of the Indo-Pacific region have employed a variety of monitoring techniques, including timed swim searches (Pearson and Endean 1969, Kenchington 1976), spot checks (Pearson 1972), manta tows (Moran *et al.* 1988, Oliver *et. al.* 1995, Sweatman *et. al.* 1998). However, few of these surveys have provided accurate estimates of population densities and age structures (Birkeland and Lucas 1990). Consequently, population field and modelling studies have suffered from the resulting lack of suitable data. Such information is, however, critical for improving our understanding of the possible factors and mechanisms that may be implicated in initiating outbreaks.

Accurately assessing low density populations or populations with substantial numbers of small juvenile starfish has posed particular difficulties. Juvenile *A. planci* (est. age 1), because of their cryptic behaviour and nocturnal feeding habits, are not easily sampled and have been rarely seen in the field (Doherty and Davidson 1988, Johnson *et al.* 1991). Consequently,

broad-scale survey techniques such as manta towing are considered inadequate to detect the initial stages of an outbreak (Moran and De'ath 1992, Bass and Miller 1995). Ayling and Ayling (1991) showed that transect-based benthic surveys might be more suitable for accurately censusing low-density populations of the starfish. Benthic belt transects have recently been used on the Great Barrier Reef in an attempt to provide more reliable estimates of population densities and associated age structures (Engelhardt *et. al.* 1997, 1999, 2000, Mapstone *et. al.* 1998, Mapstone and Ayling 1998). Using an intensive, transect-based methodology the most recent, third recorded outbreak episode, was detected much earlier than had previously been possible (Engelhardt *et. al.* 1997).

This report outlines the results of intensive fine-scale surveys of *A. planci* and associated live hard coral cover conducted on 9 mid-shelf reefs in the Cairns Sections of the Great Barrier Reef Marine Park (GBRMP) in 2000-01.

1.2 Objectives

Specifically, the surveys' objectives were to:

1. Obtain estimates of *A. planci* population densities and associated live hard coral cover on mid-shelf reefs in the survey area;
2. Determine size-frequency distributions within *A. planci* populations to facilitate the identification of probable age classes or 'pseudo-cohorts';
3. If present, detect early signs of possible new and emerging outbreaks to provide an early warning of likely future trends; and

The implications of our results for future monitoring and targeted research activities are discussed.

2. MATERIALS AND METHODS

2.1 Latitudinal band

We surveyed 9 mid-shelf reefs located across a latitudinal band from 14°31'S in the north (Rocky Islets Reef (b)) down to 16°48'S in the south (Thetford Reef). All reefs surveyed in 2000-01 were located along a mid-shelf trajectory with individual reefs surveyed between March and May 2001.

2.2 Individual survey reefs

Since their inception in 1994-95, fine-scale surveys of *A. planci* have focussed on mid-shelf reefs only because scientific modelling of the hydrodynamic characteristics of the central GBR region (latitudes 14°30'-19°30'S) have postulated strong but variable connectivity between reefs on this shelf position (Black and Moran 1991, Bode *et al.* 1992, Burrage *et al.* 1994). In contrast, it has been hypothesised that the inner and outer shelf reefs in this region are hydrodynamically more isolated (Black and Moran 1991, Bode *et al.* 1992), suggesting that they are seldom exposed to competent *A. planci* larvae from upstream sources. Most field data on *A. planci* distribution across the GBR also indicate a propensity of mid-shelf reefs to support larger numbers of starfish than either inner- or outer-shelf reefs (Moran *et al.* 1992, Engelhardt, *unpublished data*).

All mid-shelf reefs surveyed since 1994-95 have been selected haphazardly and without having any prior knowledge of COTS activity levels. However, over the past 6 years both logistic and operational considerations have resulted in a number of modifications to the original set of survey reefs. Reasons for either having dropped or added individual reefs to the program include the following:

- Some reefs were dropped due to the initiation of localised *A. planci* control programs that had the potential to modify the natural dynamics and characteristics of the local starfish population;
- Some reefs were dropped to accommodate the staged southward expansion of the survey area. Budget constraints did not allow for the retention of all previously surveyed reefs;
- Some reefs were dropped due to logistic and/or operational difficulties such as highly patchy distribution of suitable continuous reef habitats or an exceedingly large reef structure with a corresponding need for excessive travel away from the mother ship;

- Some reefs or individual reef zones were not surveyed during certain years due to severe weather conditions and/or cyclonic activity in the survey area.

In all instances, modifications to the sampling program were implemented following close consultation with members of the Crown-of-Thorns Starfish Research Committee (COTSREC) - an independent advisory body providing expert advice in relation to the starfish to the Great Barrier Reef Marine Park Authority (GBRMPA).

The 2000-01 surveys focussed exclusively on a sub-set of 9 reefs that had been surveyed every year since the inception of the fine-scale surveys in 1994-95. A complete overview of all individual reefs surveyed using the fine-scale methodology since 1994-95 is provided in Appendix A.

2.3 Within-reef zones

At each individual survey reef we sampled an equal number of sites and replicate transects within each of two distinct within-reef zones - the protected back reef zone (BR) and the exposed front reef zone (FR). Generally, the exposed front reef zone was defined as reef areas facing more or less directly southeast into the direction of the prevailing winds that affect the Great Barrier Reef region for most of the year. Conversely, the back reef zone comprises those parts of a reef that are largely protected from the southeasterly winds and associated wave action. Both reef zones typically include a more or less continuous and distinct solid reef edge as well as isolated reef outcrops or bommies.

2.4 Sites and replicate transects

At each survey reef, two teams of SCUBA divers were used to independently survey a total of 10 individual sites within each the two within-reef zones identified. A comprehensive methodological study by Mapstone and Ayling (1998) showed that, for visually assessing the abundance of discrete benthic organisms such as *A. planci*, belt transects measuring 50 x 5 metres often provide the least biased density estimates, particularly within the logistic and operational constraints of many survey programs. We sampled two replicate 50 x 5 metre (250 m^2) transects at each site. Both site selection and transect placement were haphazard at all times.

Transects were placed at an oblique angle down the available reef substratum from as shallow as possible (typically 1-2 m depth) to a maximum depth of 15 metres. To improve the accuracy of starfish density estimates, observers searched transects intensively as two 2.5 metre wide lanes. Where necessary, the position of marginal individuals relative to the transect was confirmed using a 2.5 metre tape measure placed at right angles to the transect line. Starfish were considered to be within the transect area when a minimum of 50% of their total body surface area was located inside the transect. For each transect the total number and size(s) of all *A. planci* present was recorded. Starfish size was measured as maximum body diameter (central disc plus extended arms) to the nearest centimetre. Accurate size measurements using rulers or tape measures were obtained where starfish were exposed and easily accessible, while sizes were estimated where starfish were partially or totally hidden.

A visual estimate of total live hard coral cover (LHCC) within each transect was also recorded. LHCC estimates were recorded as '10%-range estimates', that is coral cover was assigned to a cover category with a 10%-range (i.e. 5-15%, 25-35%, 40-50% etc.) The only exception to this rule was the use of a single 5%-range estimate where LHCC was found to be extremely low and was estimated to be less than 5% live cover. For calculating the mean percent cover of live hard coral across individual reef zones and reefs, we used the midpoints of the range estimates obtained (i.e. a value of 10% was used where the range estimate was recorded as 5-15%). The estimation error was set at $\pm$5%. Note that in all cases, the standard error (S.E.) for calculated visual LHCC estimates was actually less than the 5% margin set here. However, we decided that the more conservative, higher error margin would more accurately reflect the typically high spatial variability of benthic reef organisms including hard corals (Mapstone *et. al.* 1998). A complete overview of the survey and sampling design used in 2000-01 is provided in Table 1.

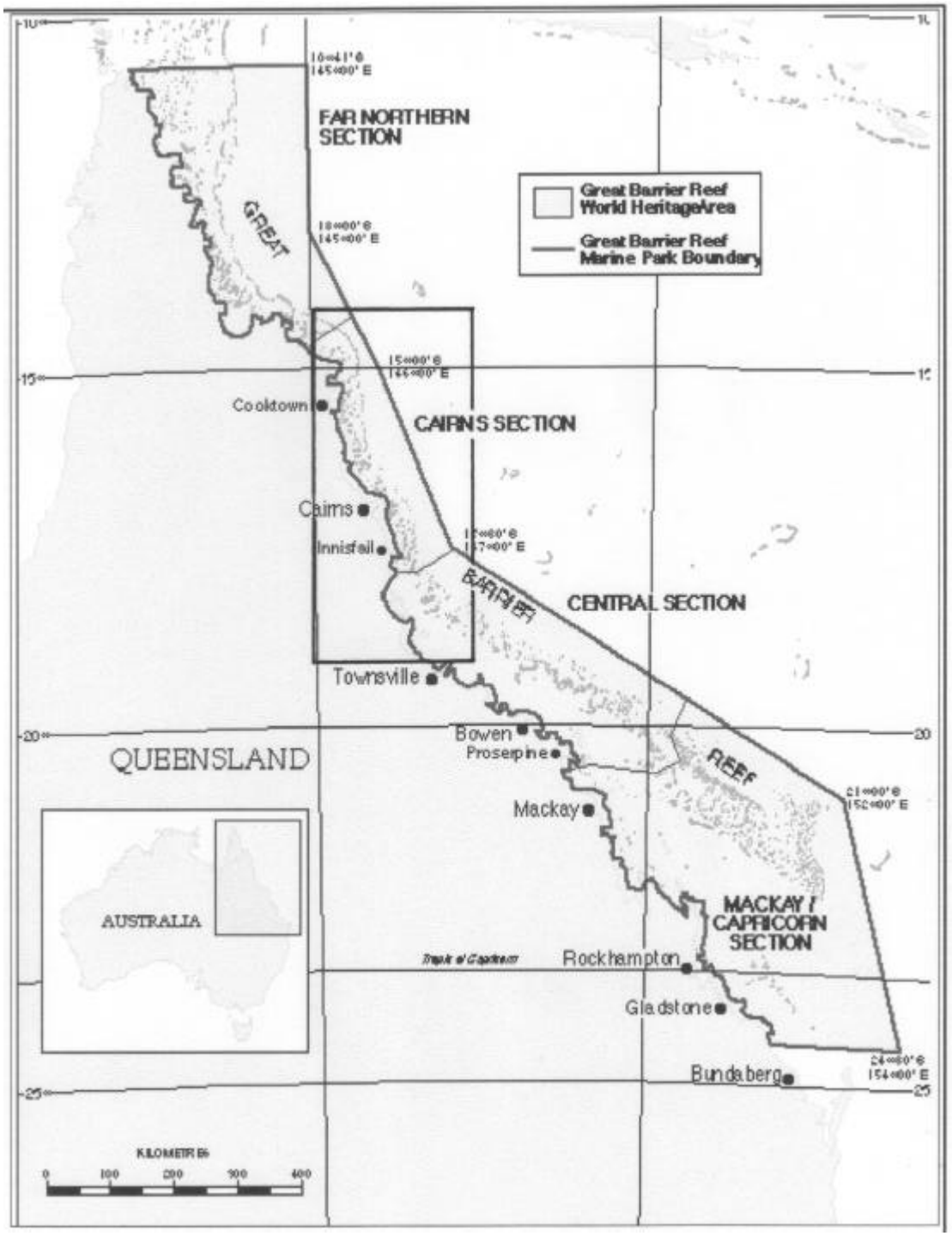


Figure 1: Map of the Great Barrier Reef Marine Park (GBRMP) showing the location of the 2000-01 survey area (central boxed area) within the Cairns Sections of the GBR Marine Park.

Latitudinal band	Reef ID number [1]	Reef name	Zones per reef	Sites x zones
(14°31'-16°48'S)	14-132b	Rocky Islets Reef	BR / FR	10 x 2
	15-109	Long Reef	BR / FR	10 x 2
	15-024	Mackay Reefs	BR / FR	10 x 2
	15-070 *	Unnamed Reef *	BR	10 x 1
	15-084	Irene Reef	BR / FR	10 x 2
	15-095 *	Evening Reef *	BR	10 x 1
	16-023	Rudder Reef	BR / FR	10 x 2
	16-024 *	Unnamed Reef *	BR	10 x 1
	16-068	Thetford Reef	BR / FR	10 x 2
TOTALS:	**9 reefs**		**15 zones**	**150 sites 300 transects**

[1] ***Reef ID numbers as per GBRMPA Reef Gazetteer***

Table 1: Overview of the sampling design used for *A. planci* fine-scale surveys in 2000-01. Reefs marked * indicate that, due to severe weather conditions, only the back reef zone was sampled.

2.5 Estimation of probable age classes of *A. planci*

In the absence of reliable ageing techniques for *A. planci,* probable ages of individual starfish were estimated by fitting size measurements or estimates to a previously constructed probable 'size-at-age' curve for *A. planci* in the central Great Barrier Reef (Figure 2). This curve had been constructed using detailed size-frequency information from more than 3,500 individual starfish recorded and measured during previous surveys (Engelhardt, unpublished data). In line with accepted convention, distinct peaks (modes) apparent in the size-frequency distribution of the target organism, in this case *A. planci,* were deemed to be indicative of probable age classes or 'pseudo-cohorts'. The identified 'pseudo-cohorts' were used again here to assign individual *A. planci* observed in 1999-00 to one of three probable age classes - juvenile

starfish (estimated age 1, ≤13 cm), sub-adult starfish (estimated age 2, 14-25 cm) and adult starfish (estimated age 3 or older, ≥26 cm). The broad size/age categories used here correspond well with other published information on probable size and age relationships in *A. planci*. These include natural, *in situ* (Zann *et al.* 1987, 1990, Zann and Vuki 1992) as well as laboratory-based estimates of 'size-at-age' (Yamaguchi 1974, Lucas 1984). Whilst published estimates *A. planci* growth show some variability, for example 12-months old starfish may range from approximately 4.5-11.5 cm across, with 24-month old starfish most commonly in the range of 15-24 cm, they do provide a useful tool for assessing recent recruitment history.

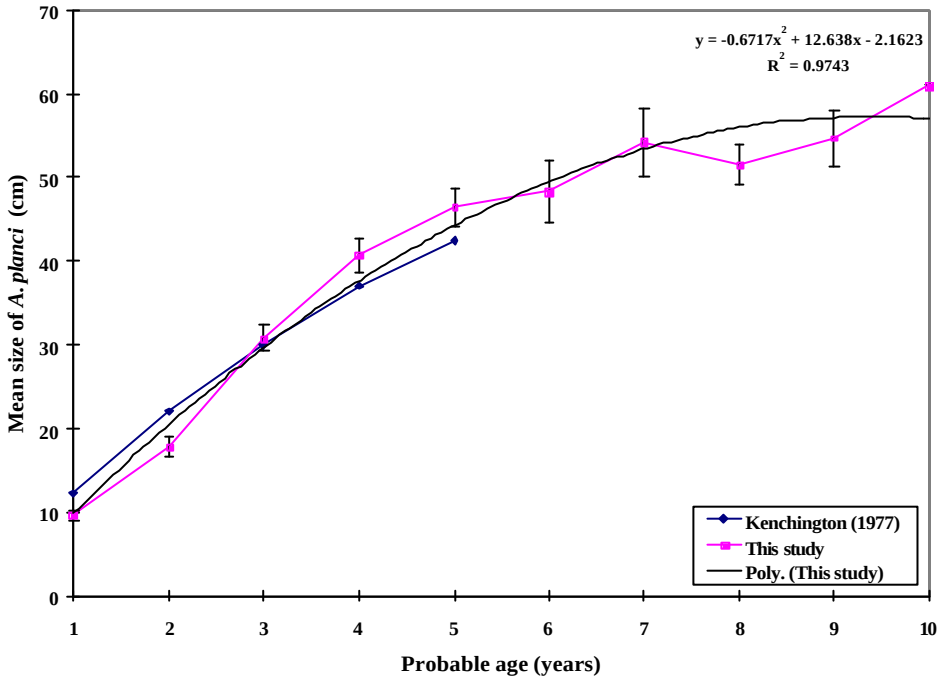


Figure 2: Estimated size-at-age plot for *A. planci* in the central Great Barrier Reef region. Error bars show standard errors (±1 S.E.). Note that the term 'Poly.' as shown in the legend refers to the 2nd-order polynomial function used to fit the curve for this study's data set.

2.6 Determination of reef status

Reefs were classified as sustaining actively outbreaking populations of *A. planci* if the mean density (minus 1 standard error S.E.) of adult starfish was ≥0.75 individuals per 250 m^2 transect. This upper threshold level for a sustainable population density of *A. planci* is based on *in situ* observations and subsequent calculations of *A. planci* feeding rates. Keesing (1990) and Keesing and Lucas (1992) suggested that a density of between 10 and 15 adult *A. planci* per 10,000 m^2 (1 hectare) could be sustained in areas with 20-50 % live coral cover (equals a mean adult density of between 0.25 and 0.375 per 250 m^2). The higher threshold of 0.75 individuals per 250 m^2 used in this study is more conservative and takes some additional

variables, such as possibly higher coral cover and seasonally reduced feeding rates into account.

Determination of individual reef classifications followed a hierarchical principle as summarised in Table 2. Selected data sub-sets were analysed in the exact order shown in Table 2, that is the ADULT sub-set first, the SUB-ADULT AND ADULT set second, the JUVENILE sub-set next and so on, with the identified highest order classification used to define reef or zonal status.

Data sub-set	Classification criteria	Reef status category
Step 1.1 **ADULT** *A. planci* counts only (≥26 cm max. diameter), back reef **OR** front reef transects only.	**IF** mean density of **ADULT** *A. planci* (minus 1 standard error) **IS** ≥ 0.75 individuals per 250 m^2 in **EITHER** back **OR** front reef zone	**THEN** **A**ctive **S**pot **O**utbreak **ASO (BR) / ASO (FR)** (current outbreak)
Step 1.2 **ADULT** *A. planci* counts only (≥26 cm max. diameter).	**IF** mean density of **ADULT** *A. planci* (minus 1 standard error) **IS** ≥ 0.75 individuals per 250 m^2 in **BOTH** back **AND** front reef zone	**THEN** **A**ctive **O**utbreak **AO** (current outbreak)
Step 2.1 **SUB-ADULT AND ADULT** *A. planci* counts combined (≥14 cm max. diameter), back reef **OR** front reef transects only.	**IF** mean density of **SUB-ADULT AND ADULT** *A. planci* combined (minus 1 standard error) **IS** ≥ 0.75 individuals per 250 m^2 in **EITHER** back **OR** front reef zone	**THEN** **I**ncipient **S**pot **O**utbreak **ISO (BR) / ISO (FR)** (active spot outbreak within 6 to 12 months)
Step 2.2 **SUB-ADULT AND ADULT** *A. planci* counts combined (≥14 cm max. diameter).	**IF** mean density of **SUB-ADULT AND ADULT** *A. planci* combined (minus 1 standard error) **IS** ≥ 0.75 individuals per 250 m^2 in **BOTH** back **AND** front reef zone	**THEN** **I**ncipient **O**utbreak **IO** (active outbreak within 6 to 12 months)
Step 3.1 **JUVENILE** *A. planci* only (≤13 cm max. diameter), back reef **OR** front reef transects only.	**IF** mean density of **JUVENILE** *A. planci* (minus 1 standard error) **IS** ≥ 2.5 individuals per 250 m^2 in **EITHER** back **OR** front reef zone	**THEN** **F**uture **S**pot **O**utbreak **FSO (BR) / FSO (FR)** (incipient spot outbreak within 6 to 12 months; active spot outbreak within 18 to 24 months)

Step 3.2 **JUVENILE** *A. planci* only (≤13 cm max. diameter).	**IF** mean density of **JUVENILE** *A. planci* (minus 1 standard error) **IS** ≥ 2.5 individuals per 250 m^2 in **BOTH** back **AND** front reef zone	**THEN** **F**uture **O**utbreak **FO** (incipient outbreak within 6 to 12 months; active outbreak within 18 to 24 months)
Step 4.1 Post-outbreaking reef(s)	**IF NONE** of the above classifications apply to any of the data sub-sets **BUT** the reef or reef zone **HAS** recently (within the last 5 years) been classified as actively outbreaking (**AO / ASO** category assigned)	**THEN** **P**ost **O**utbreak **PO / PSO(BR/FR)** respectively
Step 4.2 Non-outbreaking reef(s)	**IF NONE** of the above classifications apply to any of the above data sub-sets **AND** the reef or reef zone **HAS NOT** recently (within the last 5 years) been classified as actively outbreaking.	**THEN** **N**on-**O**utbreaking **NO / NSO (BR/FR)** respectively

Table 2: Reef status classification scheme - overview of data sub-sets and criteria used to determine the status of individual reefs and within-reef zones surveyed in 2000-01.

The threshold value of 2.5 (mean-1 S.E.) individual juvenile *A. planci* per 250 m^2 used to define possible Future spot and/or reef-wide outbreaks (FSO/FO respectively) is based on relevant observations made over the past six survey seasons. In some instances, average juvenile densities of approximately 1.25 individuals per transect have provided a reliable early indication of new and emerging outbreaks (Engelhardt, *unpublished data*). However, we decided to use a more conservative average figure of 2.5 juveniles per transect before assigning the Future Outbreak classification to any of the reefs surveyed in 1999-00. Throughout the report we refer to juvenile densities of between 1.25 and 2.5 (mean-1 S.E.) individual juvenile *A. planci* per 250 m^2 as *'significant'* densities, with estimates above the critical threshold of 2.5 (mean-1 S.E.) individual juvenile *A. planci* being referred to as *'unsustainably high'* densities. Survey results are shown graphically in Figures 3.1 to 3.19.

3. RESULTS

3.1 The distribution and abundance of estimated age classes of *A. planci* in 2000-01.

Overview of results

We recorded a total of 398 *A. planci* on the 9 reefs surveyed. Juvenile starfish (est. age 1) accounted for 200 (50.3%) of these with a further 69 (17.3%) individual sub-adults (est. age 2) and 129 (32.4%) adult (est. age 3) starfish recorded in the 300 benthic transects sampled.

Adult *A. planci* (est. age 3 and older): Densities of adult starfish across individual survey reefs or zones within reefs ranged from 0.0±0.0 (reef mean ± 1 S.E.) individuals per 250 m^2 recorded on 2 reefs (14-132b and 16-024) to 2.95±0.79 individuals at Thetford Reef (16-068) - approximately 4-times above what is considered to be a sustainable density – leading to its classification as an Active Spot Outbreak (ASO). Details of adult starfish densities for individual reefs and zones within reefs are presented in Tables 3.1 to 3.19.

Sub-adult *A. planci* (est. age 2): Densities of sub-adult starfish on individual survey reefs ranged from 0.0±0.0 (reef mean ± 1 S.E.) individuals per 250 m^2 recorded at Unnamed Reef (16-024) up to 0.43±0.14 individuals recorded at Irene Reef (15-084). We detected no new Incipient Spot Outbreaks (ISO) during the 2000-01 surveys. Details of sub-adult starfish densities for individual reefs and zones within reefs are presented in Tables 3.1 to 3.19.

Juvenile *A. planci* (est. age 1): Densities of juvenile starfish across individual survey reefs ranged from 0.05±0.03 (reef mean ± 1 S.E.) individuals per 250 m^2 at Thetford Reef (16-068) to 2.25±0.39 individuals recorded at Irene Reef (15-084). Details of juvenile starfish densities for individual reefs and zones within reefs are presented in Tables 3.1 to 3.19.

Most of the Incipient Spot Outbreaks (ISO) recorded in 1999-00 appear to have failed to develop into active outbreaks of adult starfish by 2000-01. Preliminary analyses of our data suggest that a lack of suitable Live Hard Coral Cover (LHCC) on local reefs is the likely explanation for the apparent failure of sub-adult starfish to reach maturity. The records obtained from the nine core survey reefs over the past 7 years suggests that a minimum

LHCC of approximately 15% may be required to facilitate the development of a new outbreak.

3.2 Summaries of survey results for individual reefs

The following section (Figures 3.1 - 3.19) provides a detailed summary of the results of the 2000-01 fine-scale surveys for individual reefs. In addition to *A. planci* size-frequency information, we provide estimates of average densities for three age classes of *A. planci* both across entire reefs and within individual reef zones. To assist in the interpretation of recent trends in both adult starfish densities and associated live hard coral cover we show relevant time series data collected since the initiation of the survey program in 1994-95. Where reefs or zones within reefs had not been surveyed in a particular year the initials 'NS' (**N**ot **S**urveyed) are shown.

Note that visual estimates of Live Hard Coral Cover (LHCC) have only been recorded since the 1995-96 survey season. Mean LHCC estimates for 1995-96 were derived from 20%-range estimates (i.e. mid-point $\pm$ 10% set error margin). However, since 1996-97 all LHCC estimates have been recorded using higher resolution 10%-range estimates as outlined in this report's methodology section.

Aerial photographs of individual survey reefs show the locations of all sites sampled in 2000-01. Use of these aerial photographs is with permission of the GBRMPA and is covered by a formal use agreement. All reef images are oriented along a North-South axis with the top margin pointing due north. Due to the fact that the available imagery came from a variety of photographic scans of unknown magnification we were unable to provide accurate scale bars for inclusion on individual reef images.

Figure 3: Summary of results for mid-shelf reefs surveyed in 2000-01

Figure 3.1: Rocky Islets Reef (14-132b)

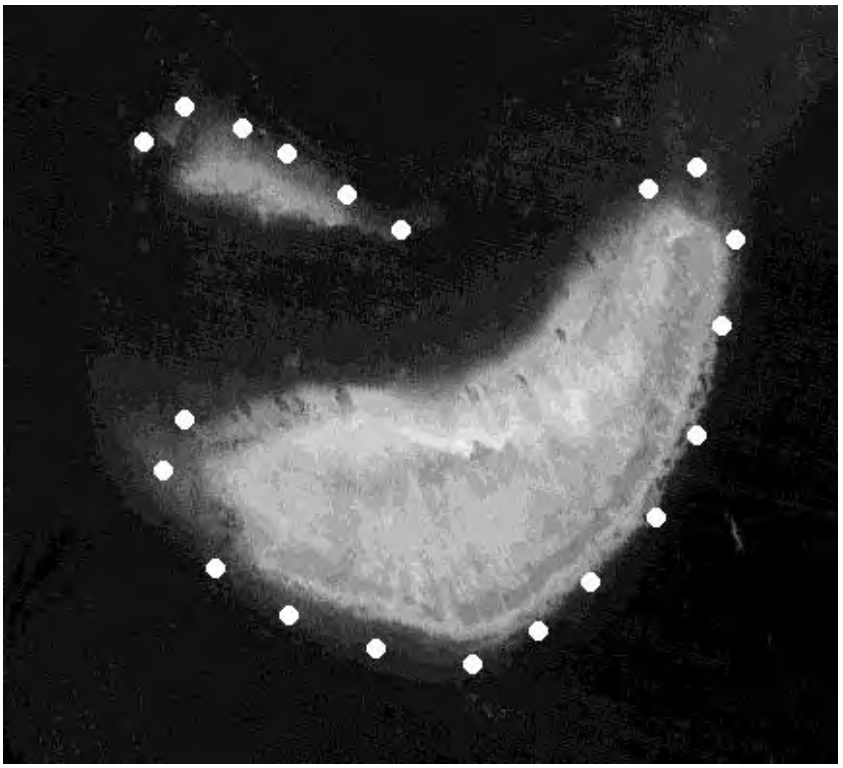


Figure 3.1.1: Aerial photograph of Rocky Islets Reef (14-132b) with white dots indicating the approximate locations of the 20 sites surveyed in March 2001.

A - Year	1994-95	1995-96	1996-97	1997-98	1998-99	1999-00
Status	IO	AO	AO	AO	PO	PO

B – 2000-01 Sample area	Juveniles (est. age 1)	Sub-adults (est. age 2)	Adults (est. age 3 or older)	Status 2000-01
Back Reef (BR)	0.10±0.07 (2)	0.10±0.07 (2)	0.00±0.00 (0)	PSO
Front Reef (FR)	0.35±0.13 (7)	0.40±0.13 (8)	0.00±0.00 (0)	PSO
Entire Reef (R = BR & FR)	0.23±0.08 (9)	0.25±0.08 (10)	0.00±0.00 (0)	PO

Table 3.1 (A-B): Summary of reef status classifications for Reef 14-132b since 1994-95 (A) and mean densities (±1 S.E.) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 2000-01 (B). Values shown in brackets are total *A. planci* counts.

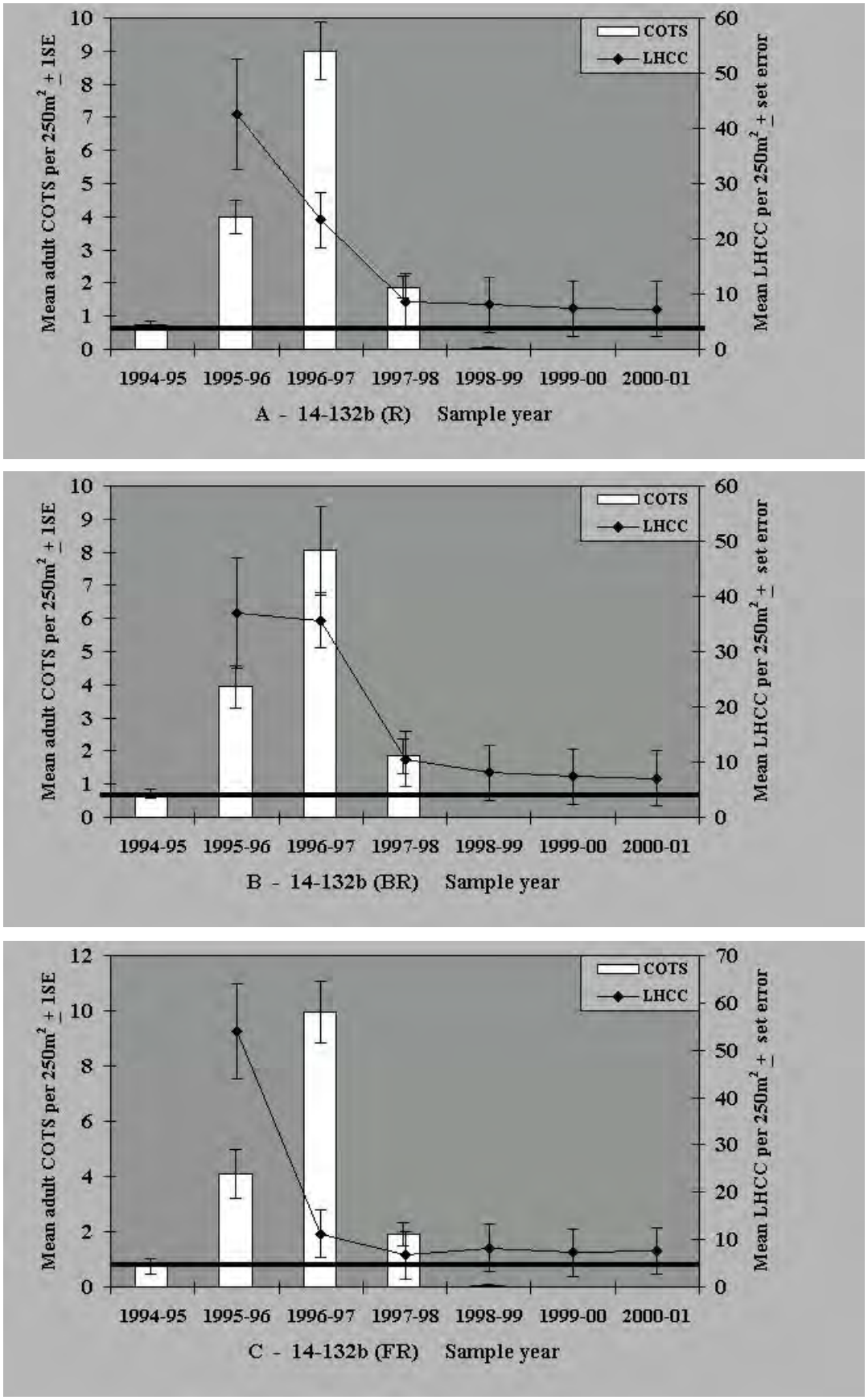
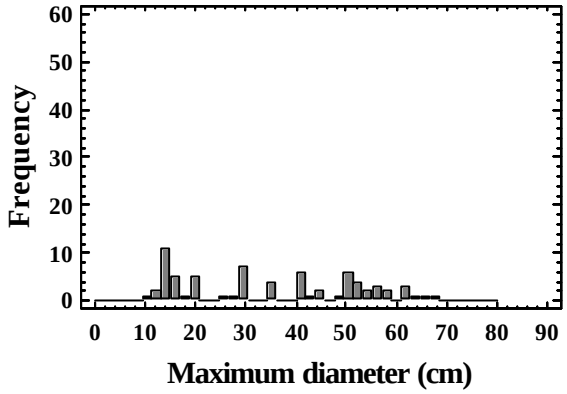
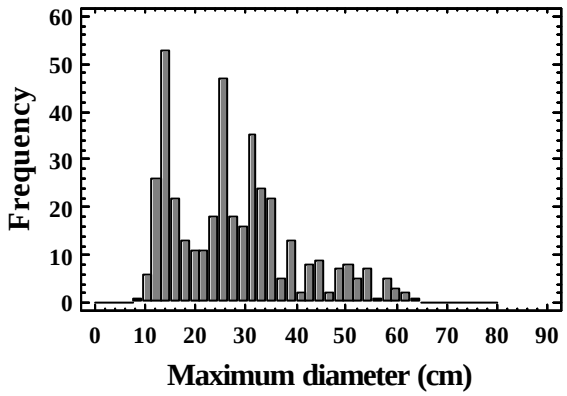


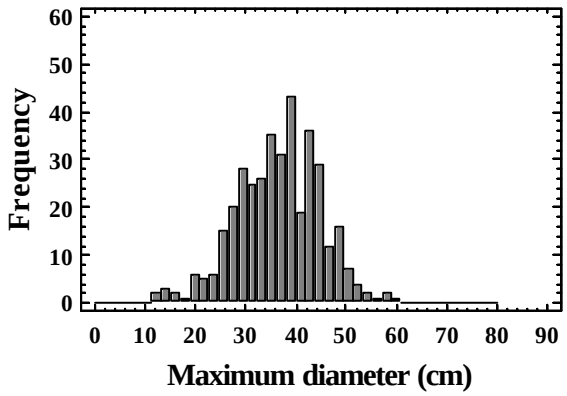
Figure 3.1.2 (A-C): Reef 14-132b - Recent trends in the mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back reef zone (B-BR) and in the front reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbre aking population.



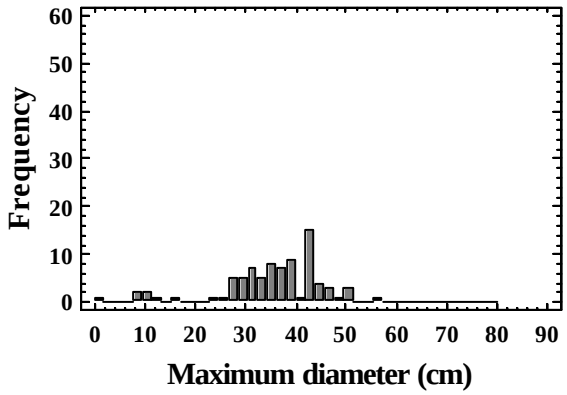
1994-95



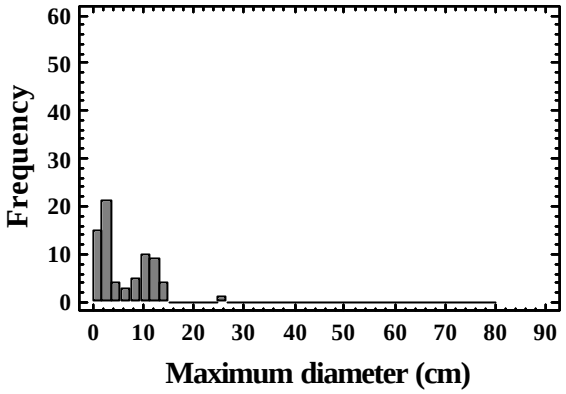
1995-96



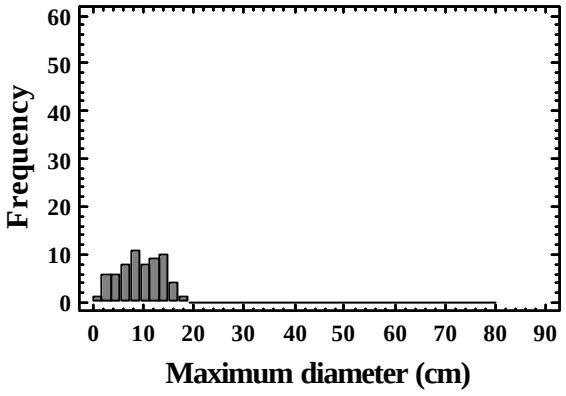
1996-97



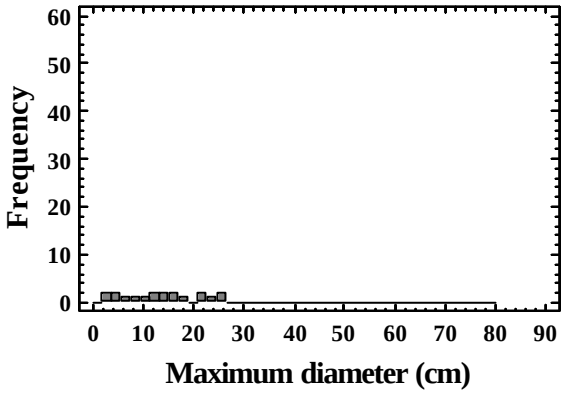
1997-98



1998-99



1999-00



2000-01

Figure 3.1.3: Size-frequency plots of *A. planci* observed at Rocky Islets Reef (14-132b) between 1994 and 2001.

Summary

Rocky Islets Reef (14-132b) experienced a severe reef-wide outbreaks of COTS from 1995 through to 1998 with peak densities of adult COTS recorded at 12-times above sustainable levels. Live hard coral cover (LHCC) across the reef declined from an average of around 45% live cover down to less than 10% cover – a loss of around 89% of the pre-outbreaking cover of live hard corals.

The outbreaking population was comprised of multiple cohorts with individual starfish ranging in size from around 8 to 68 centimeters. Distinct peaks in the size-frequency distribution of *A. planci* suggest that at least seven consecutive cohorts or individual year classes were present during this period. Following the collapse of the outbreaking population in 1997-98, recruitment of juvenile starfish continued at significant levels for another two years. The latest surveys recorded the lowest total number of starfish over the 7 years of this program. All of the 19 individual COTS recorded in 2000-01 were either juvenile (est. age 1) or sub-adult (est. age 2) starfish. The low numbers of starfish observed are unlikely to pose any significant short-term threat to the process of hard coral recovery.

Live hard coral cover (LHCC) in both the back and the front reef zone remains low with average percent cover recorded in the 0-10% range. LHCC has remained virtually unchanged since the 1997-98 surveys. At this stage there are few obvious signs of any significant hard coral recovery.

Figure 3.2: Long Reef (15-019)

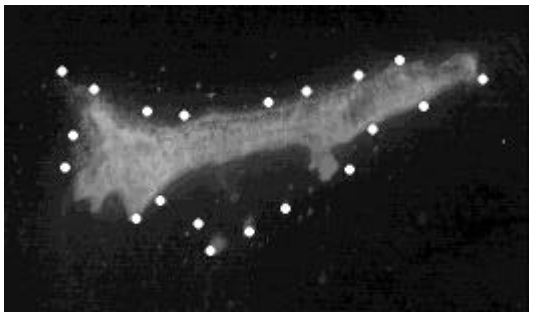


Figure 3.2.1: Aerial photograph of Long Reef (15-019) with white dots indicating the approximate locations of the 20 sites surveyed in March 2001.

A - Year	1994-95	1995-96	1996-97	1997-98	1998-99	1999-00
Status	ASO(BR) NO(FR)	AO	AO	ASO(BR) PSO(FR)	IO	IO

B – 2000-01 Sample area	Juveniles (est. age 1)	Sub-adults (est. age 2)	Adults (est. age 3 or older)	Status 2000-01
Back Reef (BR)	0.20±0.09 (4)	0.20±0.12 (4)	0.00±0.00 (0)	PSO
Front Reef (FR)	1.45±0.44 (29)	0.45±0.22 (9)	0.15±0.08 (3)	PSO
Entire Reef (R = BR & FR)	0.83±0.24 (33)	0.33±0.13 (13)	0.08±0.04 (3)	PO

Table 3.2 (A-B): Summary of reef status classifications for Reef 15-019 since 1994-95 (A) and mean densities (±1 S.E.) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 2000-01 (B). Values shown in brackets are total *A. planci* counts.

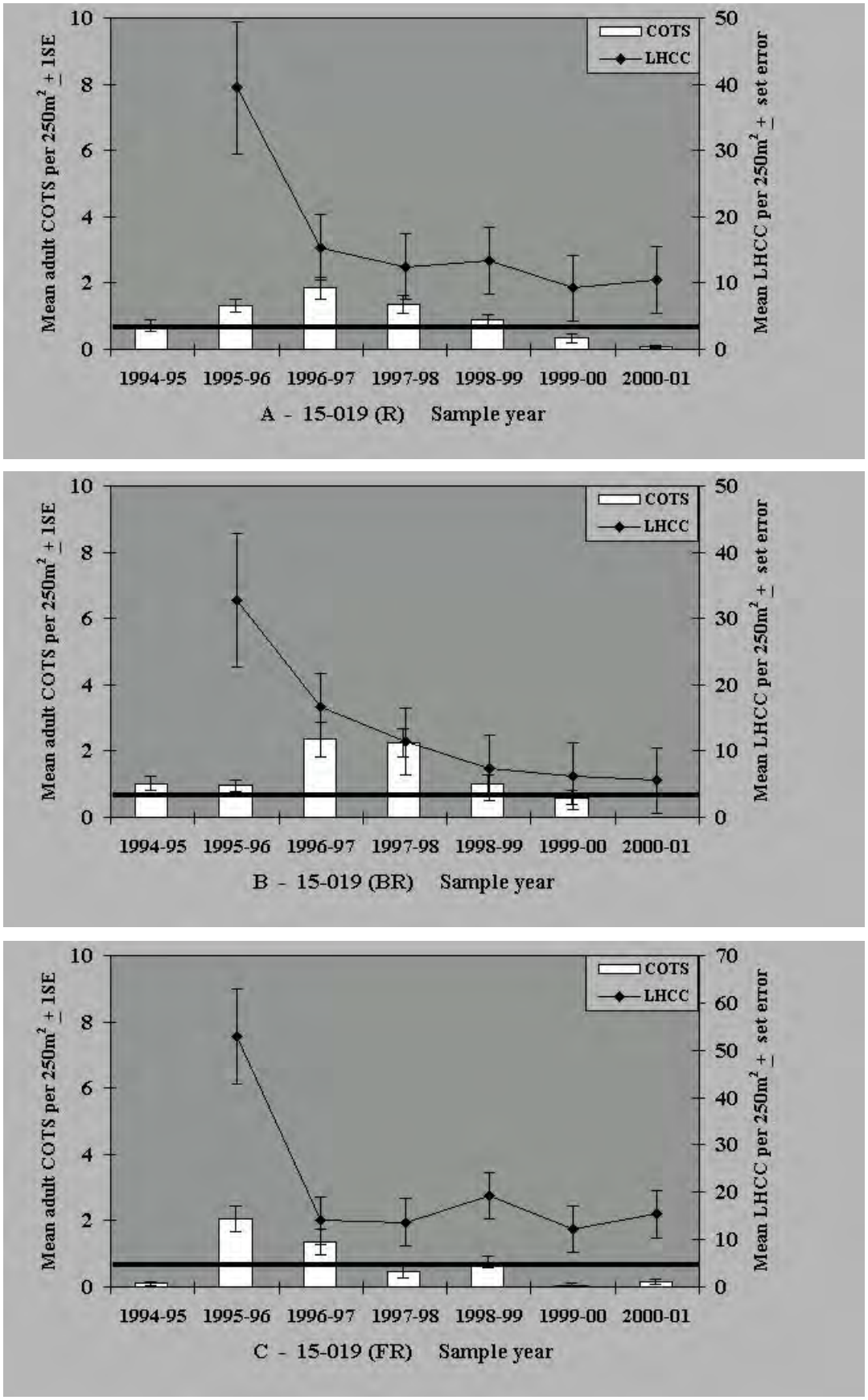


Figure 3.2.2 (A-C): Reef 15-019 - Recent trends in the mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back reef zone (B-BR) and in the front reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbreaking population.

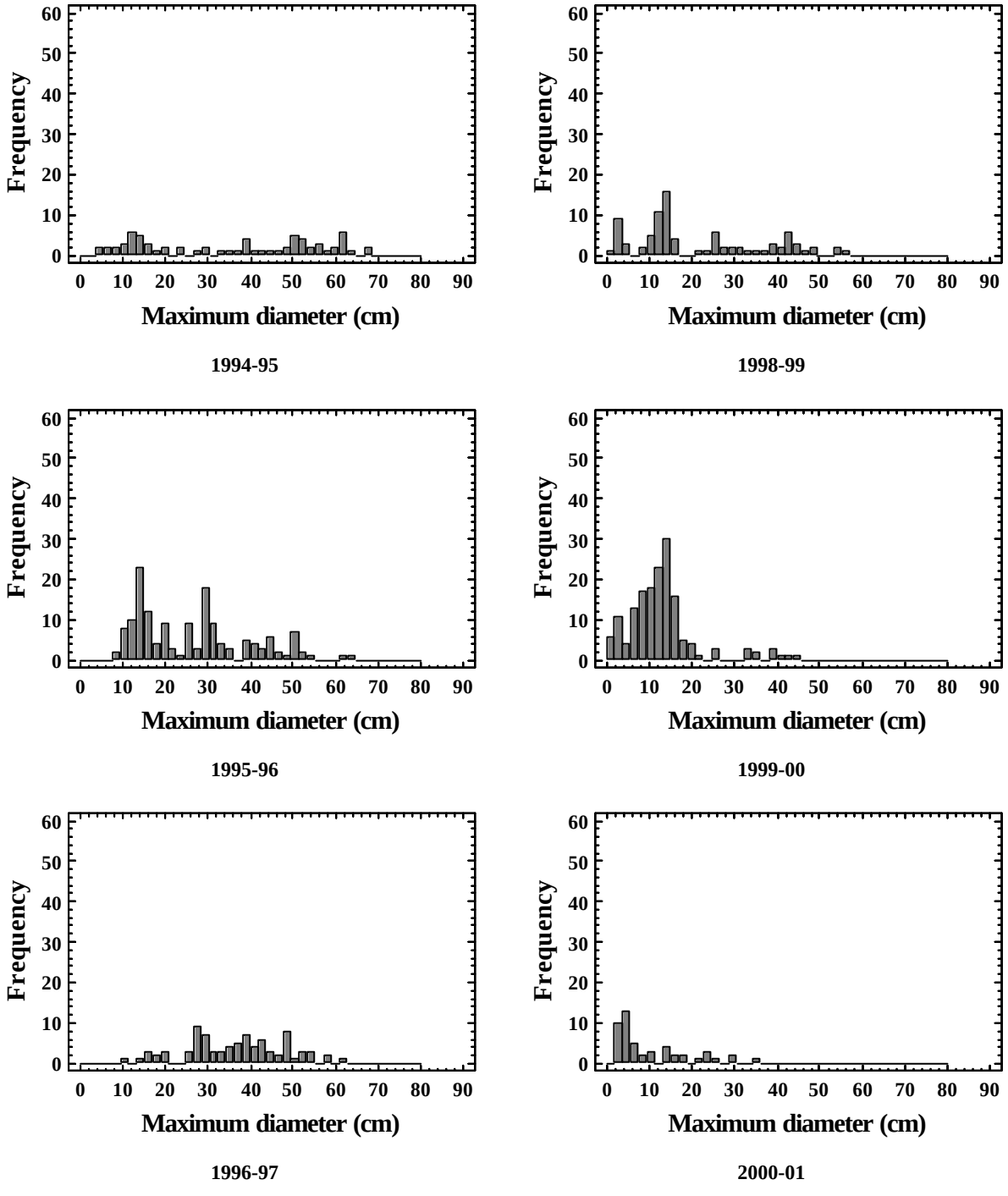


Figure 3.2.3: Size-frequency plots of *A. planci* observed at Long Reef (15-019) between 1994 and 2001.

Summary

Long Reef (15-019) experienced active spot and/or reef-wide outbreaks of *A. planci* over a 4-year period from 1994 to 1998. During this time, average live hard coral cover (LHCC) across the reef declined from pre-outbreaking levels of around 40% cover down to a remnant level of around 10% live cover – a loss of approximately 75% of the initial hard coral cover.

The back reef zone at Long Island Reef (15-019) supported near or above sustainable densities of COTS over a prolonged six-year period from 1994 through to 2000. During this time, COTS feeding activity reduced average LHCC from a value of above 30% down to the current level of only around 5% live cover.

The outbreaking population was comprised of multiple cohorts with individual starfish ranging in size from around 4 to 69 centimeters. Distinct peaks in the size-frequency distribution of *A. planci* suggest that at least five cohorts or individual year classes were present during this period. Over the past two years, recruitment of juvenile starfish has continued at significant levels. The likely future impact of these latest cohorts on the process of hard coral recovery is uncertain. Whilst the low remnant cover of hard corals is unlikely to be sufficient to allow the current population of COTS to reach maturity, there remains a significant potential for further negative impacts of COTS feeding on the process of hard coral recovery.

It is interesting to note that the high densities of sub-adult starfish (est. age 2) recorded in 1999-00 apparently failed to mature. It is highly likely that a lack of suitable coral prey was responsible for this cohorts' failure to reach maturity. A total of only 3 adult starfish was observed during the 2000-01 survey. Consequently, Long Island Reef (15-019) has now been classified as Post-Outbreaking (PO).

Figure 3.3: Mackay Reefs (15-024)

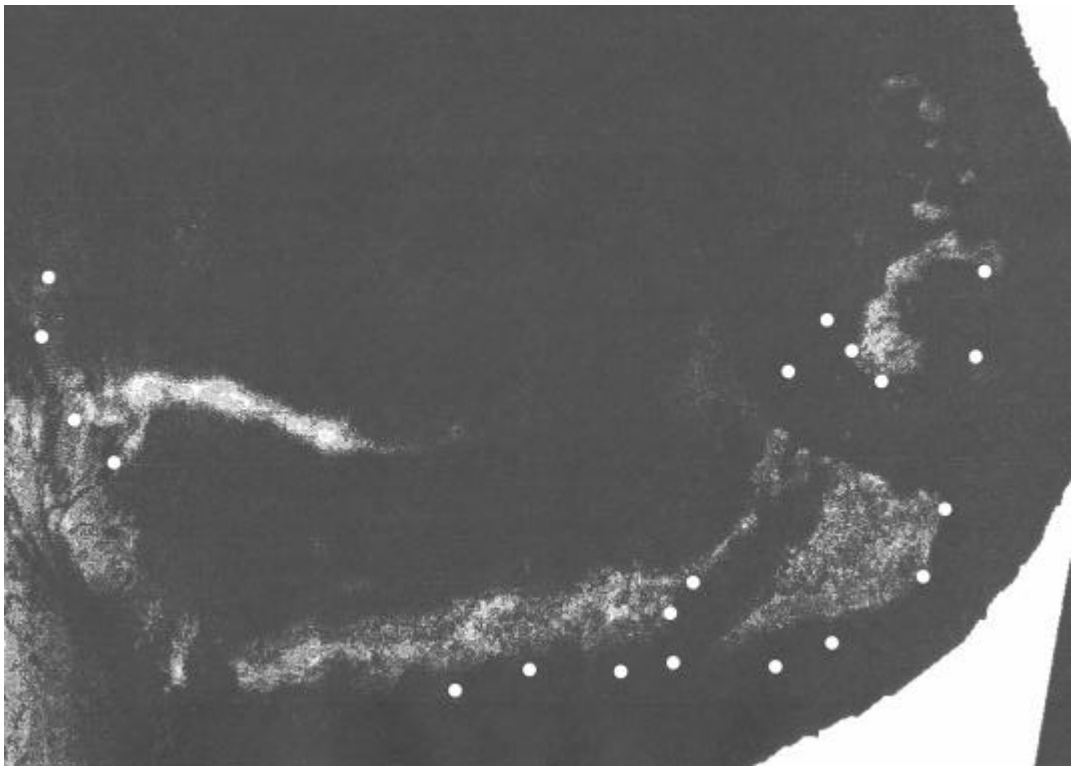


Figure 3.3.1: Aerial photograph of Mackay Reefs (15-024) with white dots indicating the approximate locations of the 20 sites surveyed in March 2001.

A - Year	1994-95	1995-96	1996-97	1997-98	1998-99	1999-00
Status	ASO(BR) NO(FR)	AO	AO	AO	ASO(BR) PSO(FR)	IO

B – 2000-01 Sample area	Juveniles (est. age 1)	Sub-adults (est. age 2)	Adults (est. age 3 or older)	Status 2000-01
Back Reef (BR)	0.25±0.12 (5)	0.15±0.08 (3)	0.05±0.05 (1)	PSO
Front Reef (FR)	1.15±0.28 (23)	0.00±0.00 (0)	0.00±0.00 (0)	PSO
Entire Reef (R = BR & FR)	0.70+0.17 (28)	0.08±0.04 (3)	0.03±0.03 (1)	PO

Table 3.3 (A-B): Summary of reef status classifications for Reef 15-024 since 1994-95 (A) and mean densities (±1 S.E.) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 2000-01 (B). Values shown in brackets are total *A. planci* counts.

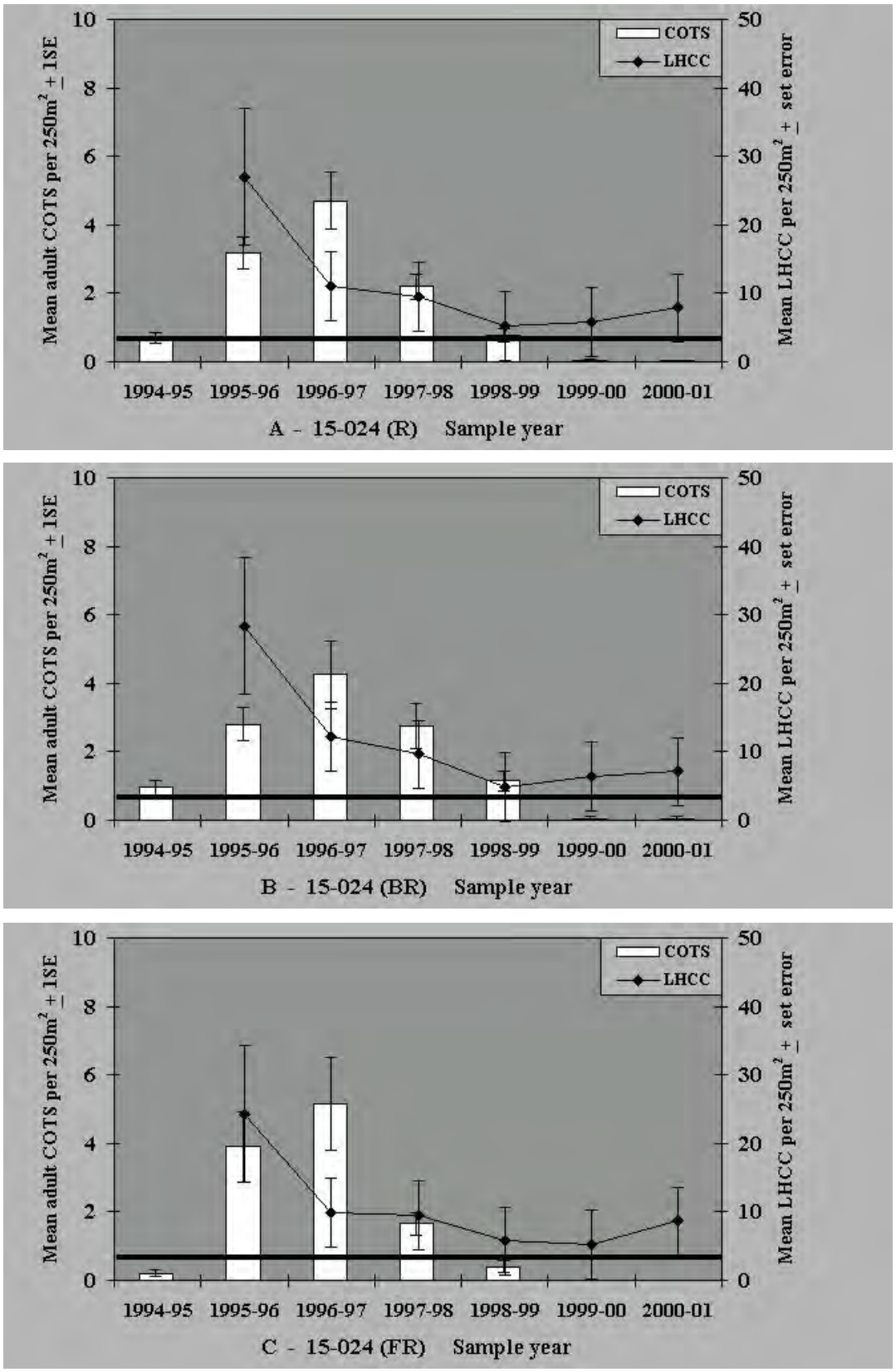


Figure 3.3.2 (A-C): Reef 15-024 - Recent trends in the mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back reef zone (B-BR) and in the front reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbreaking population.

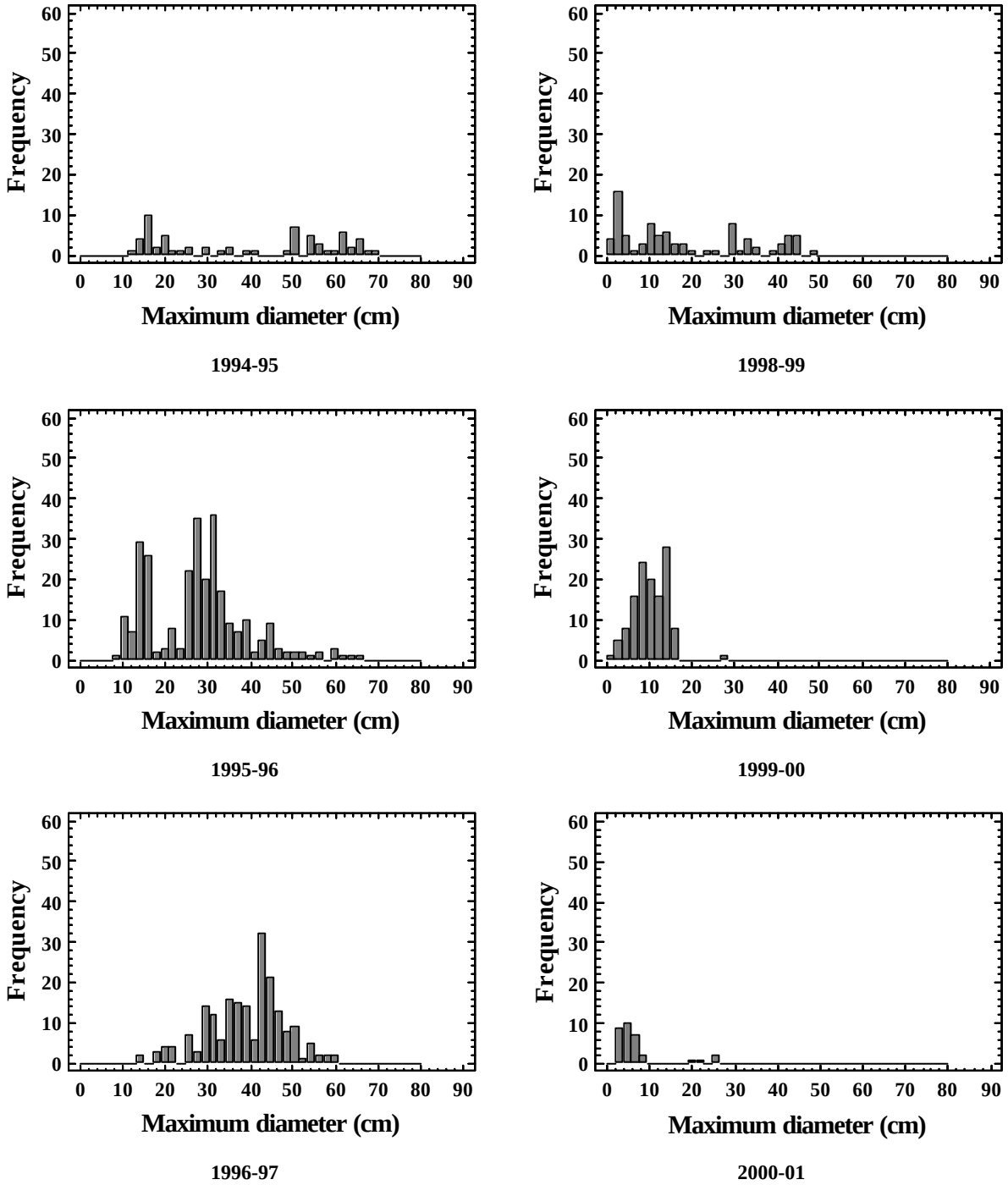


Figure 3.3.3: Size-frequency plots of *A. planci* observed at Mackay Reefs (15-024) between 1994 and 2001.

Summary

Mackay Reefs (15-024) experienced severe active spot and/or reef-wide outbreaks of *A. planci* over a 5-year period from 1994 to 1999. Peak densities of mature starfish were recorded at approximately 6.5 times sustainable levels. As a direct consequence of the intense COTS feeding activity, Live Hard Coral Cover (LHCC) declined from pre-outbreaking levels of around 25% across the reef down to a remnant level of only 5% live cover – a reduction of some 80% based on the initial LHCC. The dramatic decline in available coral cover was closely followed by a virtual collapse of the local COTS population by early 1999.

The outbreaking population of *A. planci* was comprised of multiple year classes with individual starfish ranging from around 8 to 70 cm maximum diameter. Distinct peaks in the size-frequency distribution of starfish during this period suggest that at least seven consecutive cohorts of individual year classes were present at the time. Since the collapse of the outbreaking population in 1999, recruitment of juvenile *A. planci* at Mackay Reefs has remained at significant levels. The strong 1997-98 cohort appears to have failed to reach maturity, probably as a result of the general lack of suitable hard coral prey. The likely future impact of recently settled juvenile starfish on the process of hard coral recovery remains somewhat uncertain. However, there are early indications that LHCC in the front reef zone has started to increase again which suggests that feeding impacts by small juvenile COTS have been relatively minor over the past year.

It appears that the low levels of remnant LHCC observed in 1999-00 were insufficient to sustain the large numbers of sub-adult starfish that were observed during the same period. In line with the results of the 1999-00 survey only a single adult starfish was recorded in 2000-01. The generally low numbers of juvenile and sub-adult starfish observed in 2000-01 are unlikely to pose any significant threat to the reef recovery process in the near future.

Figure 3.4: Unnamed Reef (15-070)

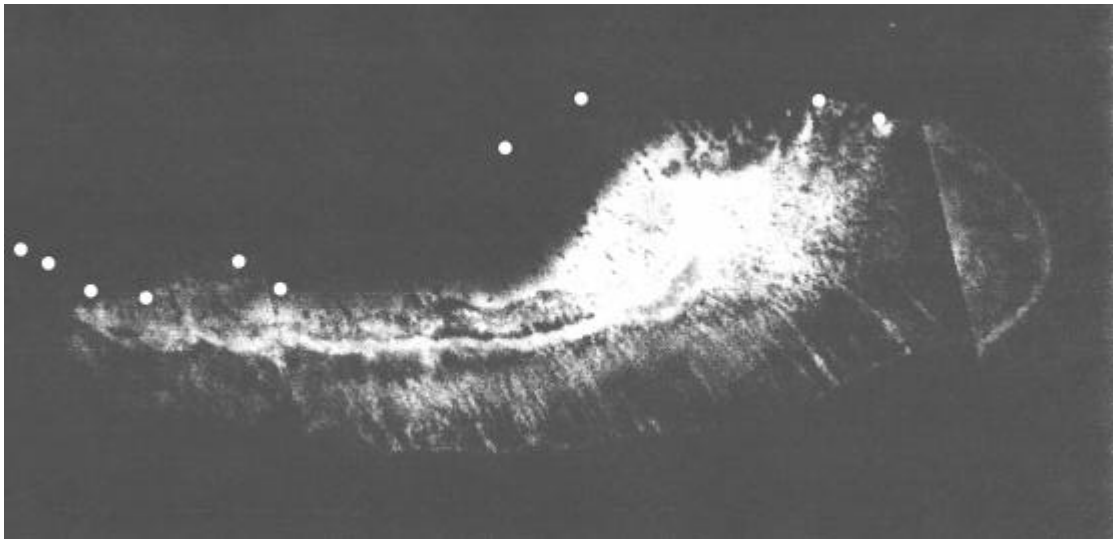


Figure 3.4.1: Aerial photograph of Unnamed Reef (15-070) with white dots indicating the approximate locations of the 10 sites surveyed in April 2001.

A - Year	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Status	NO	ASO(BR) ISO(FR)	ASO(BR) NO(FR)	ASO(BR) NO(FR)	ASO(BR) FSO(FR)	IO

B – 2000-01 **Sample area**	**Juveniles** **(est. age 1)**	**Sub-adults** **(est. age 2)**	**Adults (est.** **age 3 or older)**	**Status** **2000-01**
Back Reef **(BR)**	0.30±0.16 (6)	0.30±0.13 (6)	0.15±0.08 (3)	PSO
Front Reef **(FR)**	NS	NS	NS	NS
Entire Reef **(R = BR & FR)**	(6)	(6)	(3)	PSO(BR) NS(FR)

Table 3.4 (A-B): Summary of reef status classifications for Reef 15-070 since 1994-95 (A) and mean densities (±1 S.E.) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 2000-01 (B). Values shown in brackets are total *A. planci* counts.

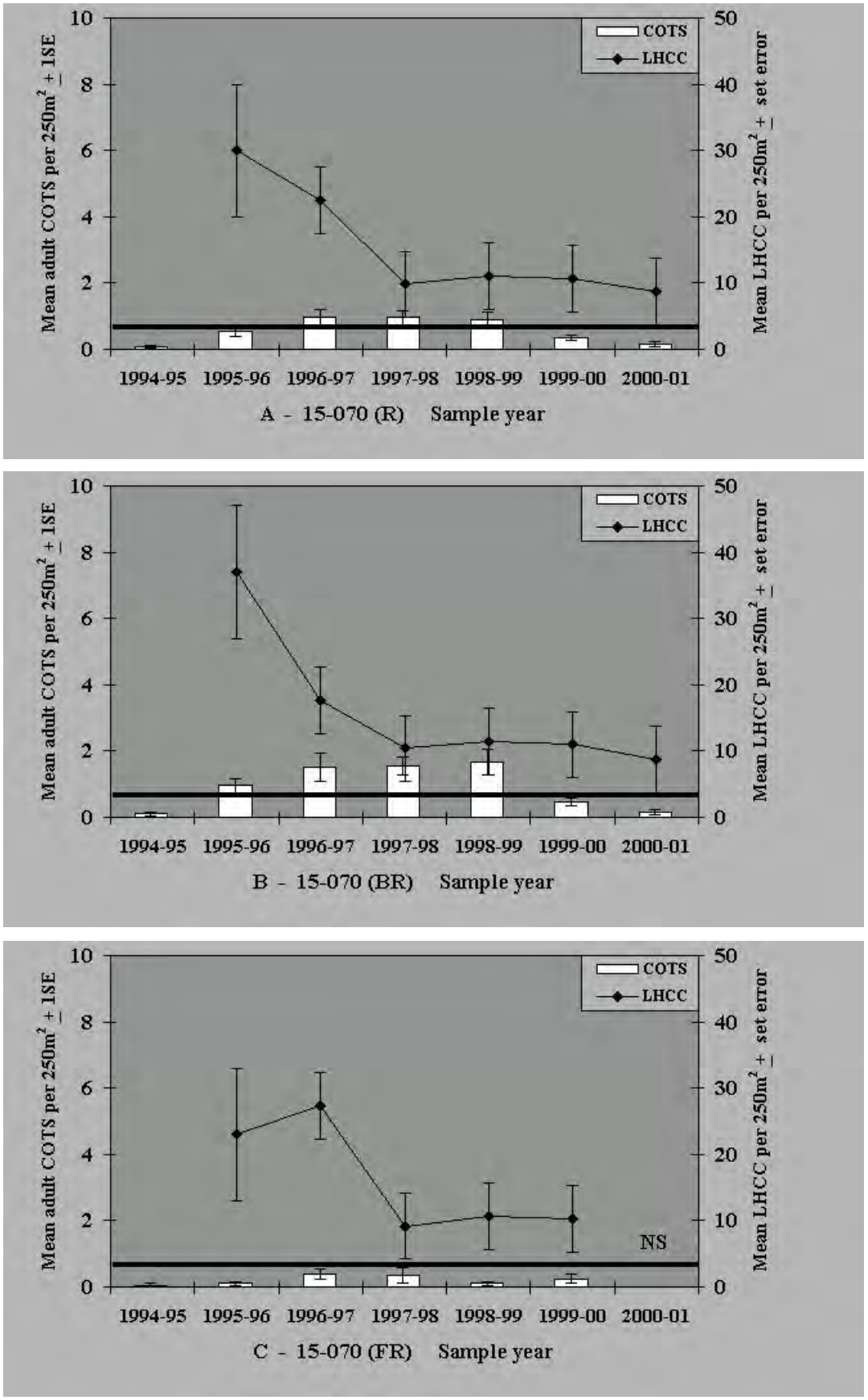


Figure 3.4.2 (A-C): Reef 15-070 - Recent trends in the mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back reef zone (B-BR) and in the front reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbreaking population.

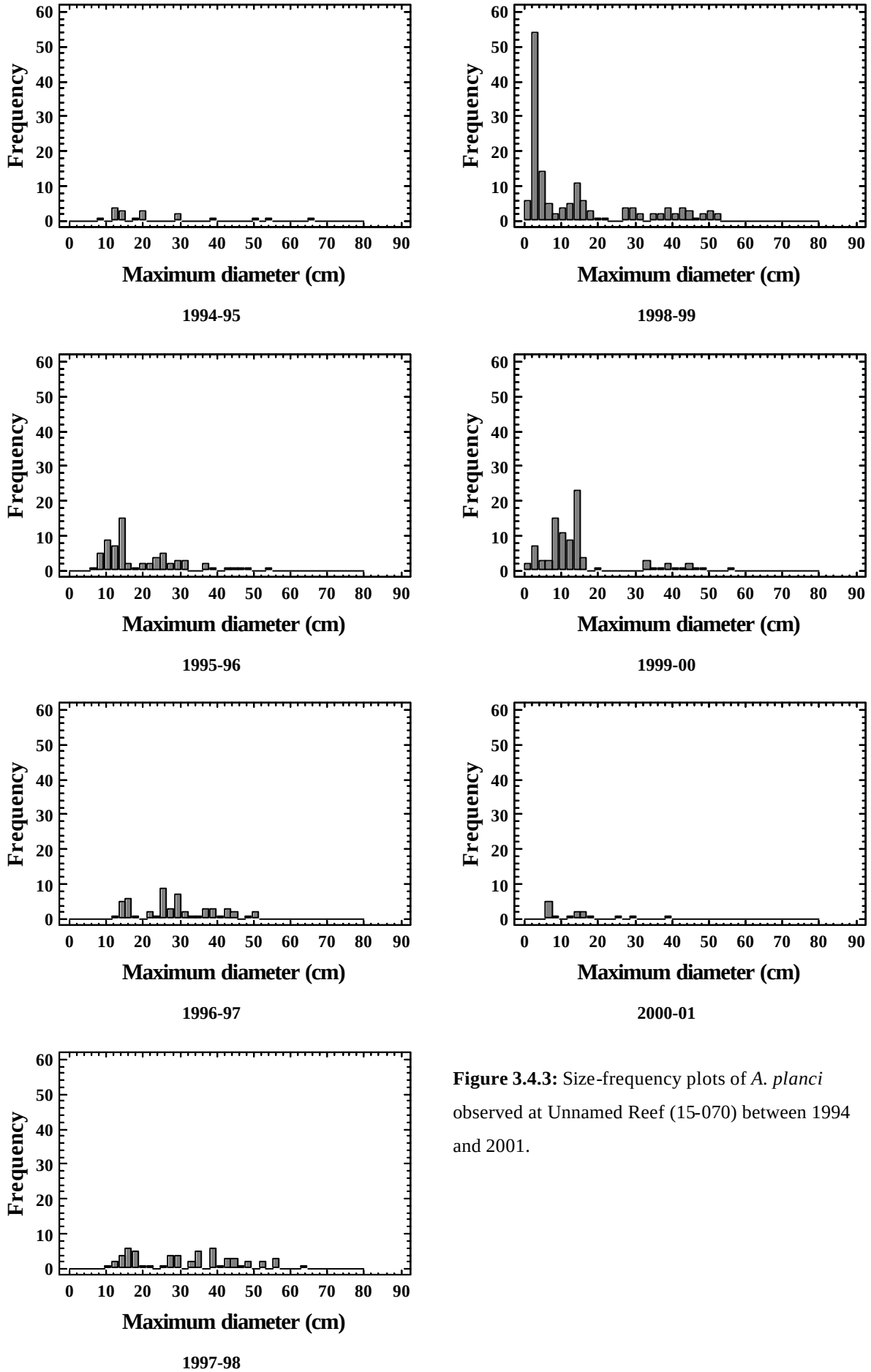


Figure 3.4.3: Size-frequency plots of *A. planci* observed at Unnamed Reef (15-070) between 1994 and 2001.

Summary

The first Active Spot Outbreak (ASO) at Unnamed Reef (15-070) was detected in the reef's back reef zone in 1995-96. Subsequently, populations of adult starfish in this zone remained at outbreaking densities for another 3 years. Peak densities of starfish in this part of the reef were recorded at levels 2-3 times above sustainable densities. During the 4-year period of the outbreak, Live Hard Coral Cover (LHCC) in the back reef zone declined from an average of around 40% cover down to the current level of around 10% live cover. Across the entire reef, LHCC was reduced from pre-outbreaking levels of around 30% live cover down to a remnant cover of around 10% - a loss of approximately 66% of the initial cover of live hard coral.

Whilst densities of adult COTS in the exposed front reef zone did not reach above sustainable levels during any of our surveys, the observed recent reduction in hard coral cover in this zone is likely to also be the result of COTS feeding activity. It is possible that large numbers of adult COTS were located outside of our predefined depth range of 1-15 meters with only occasional, sporadic incursions of these starfish into shallower water possibly resulting in the loss of live coral cover. Similar short-term incursions could have occurred in between our surveys as a result of active migration by adult starfish from the actively outbreaking back reef zone into the front reef zone.

The outbreaking population of COTS was comprised of multiple cohorts with individual starfish ranging in size from approximately 8 to 55 cm in diameter. Peaks in the size-frequency distribution of starfish during this period suggest that at least 4 cohorts or individual year classes were present.

Due to severe and persistent weather conditions we were unable to re-survey the exposed front of this reef in 2000-01. In the more sheltered back reef zone, the surveys detected only low numbers of starfish with the calculated average COTS density in this zone well below outbreaking levels. It appears that the high densities of sub-adult starfish recorded in this zone in 1999-00 have failed to mature. The remnant low live hard coral cover (LHCC) of only around 10% may have been insufficient to sustain this particular year class. The current density of starfish in the back reef zone of Unnamed Reef 15-070 is unlikely to pose any significant threat to the process of reef recovery in the near future. The back reef zone has now been classified as Post-Outbreaking (PO).

Figure 3.5: Irene Reef (15-084)

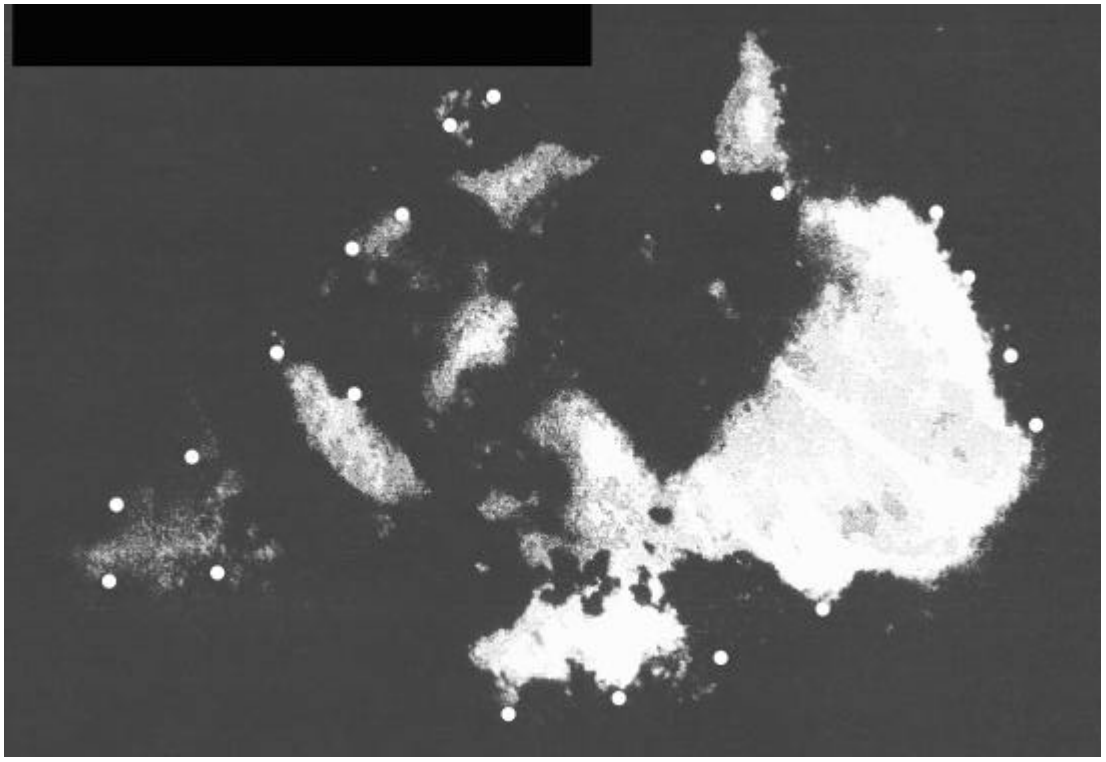


Figure 3.5.1: Aerial photograph of Irene Reef (15-084) with white dots indicating the approximate locations of the 20 sites surveyed in April 2001.

A - Year	1994-95	1995-96	1996-97	1997-98	1998-99	1999-00
Status	ASO(BR) NO(FR)	ASO(BR) ISO(FR)	ASO(BR) NO(FR)	ASO(BR) NO(FR)	PSO(BR) FSO(FR)	PSO(BR) ISO(FR)

B – 2000-01 Sample area	Juveniles (est. age 1)	Sub-adults (est. age 2)	Adults (est. age 3 or older)	Status 2000-01
Back Reef (BR)	1.25±0.39 (25)	0.55±0.23 (11)	0.05±0.05 (1)	PSO
Front Reef (FR)	3.25±0.62 (65)	0.30±0.16 (6)	0.00±0.00 (0)	NO
Entire Reef (R = BR & FR)	2.25±0.39 (90)	0.43±0.14 (17)	0.03±0.03 (1)	PSO(BR) NO(FR)

Table 3.5 (A-B): Summary of reef status classifications for Reef 15-084 since 1994-95 (A) and mean densities (±1 S.E.) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 2000-01 (B). Values shown in brackets are total *A. planci* counts.

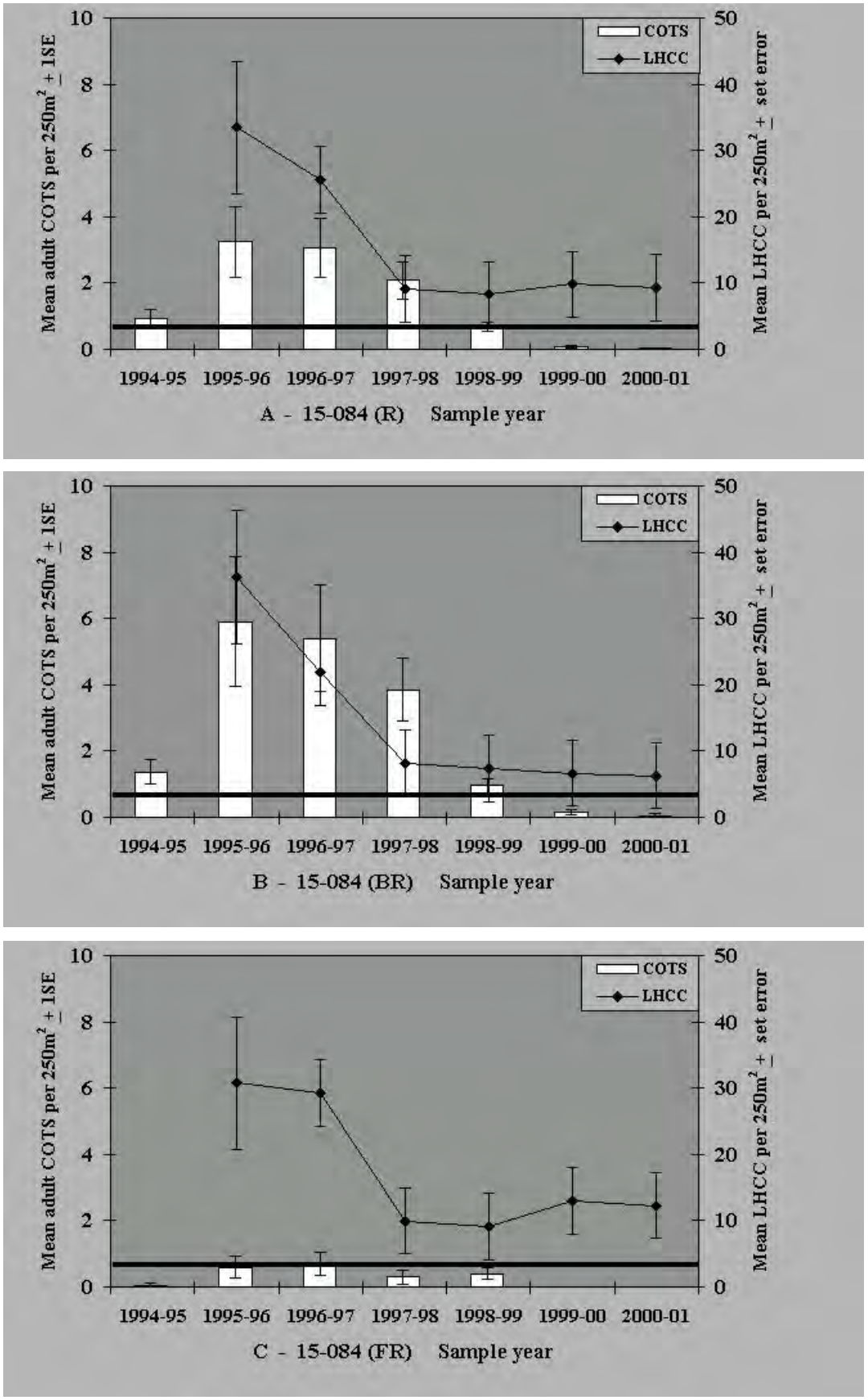


Figure 3.5.2 (A-C): Reef 15-084 - Recent trends in the mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back reef zone (B-BR) and in the front reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbreaking population.

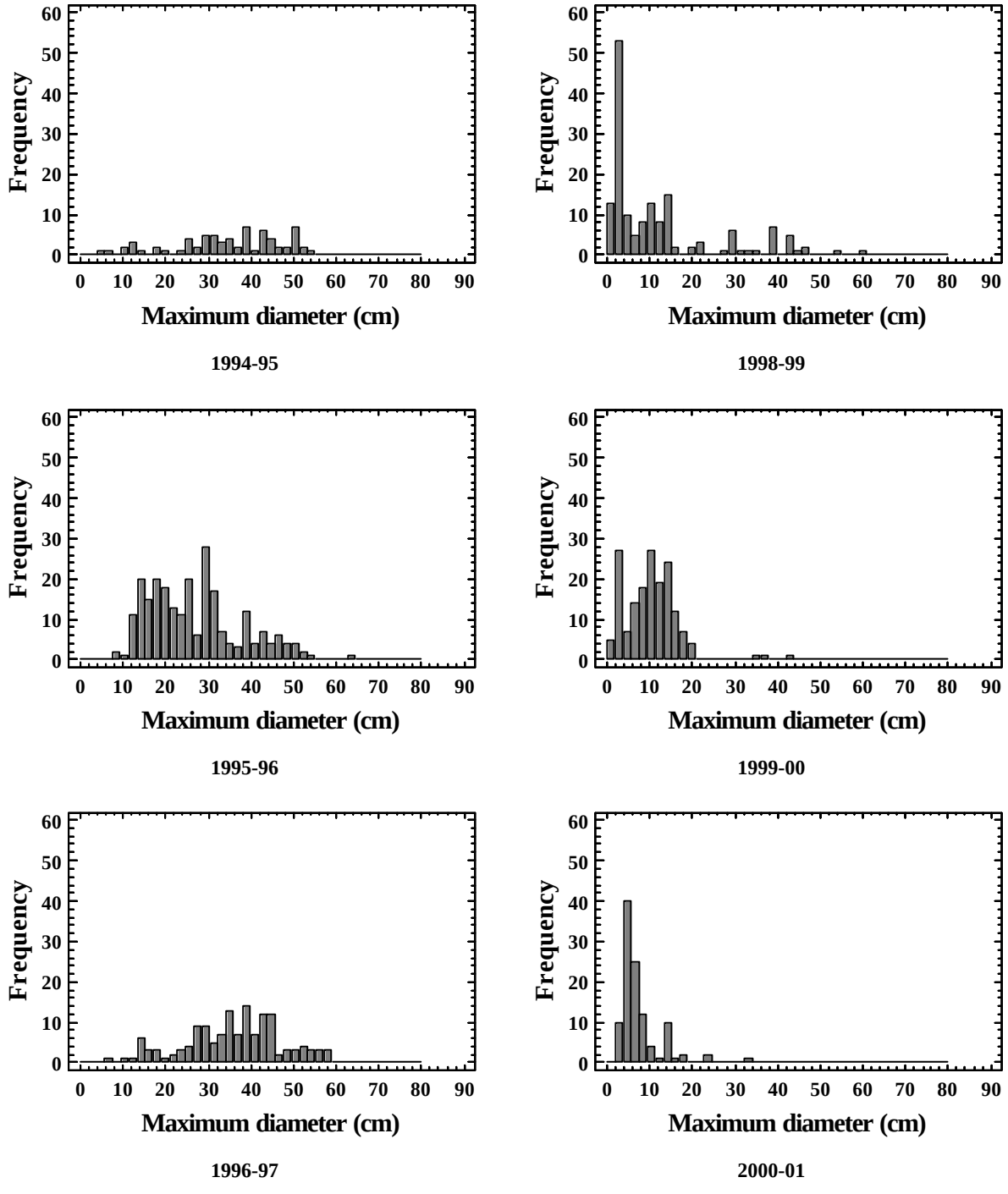


Figure 3.5.3: Size-frequency plots of *A. planci* observed at Irene Reef (15-084) between 1994 and 2001.

Summary

The severe Active Spot Outbreak (ASO) first discovered in the back reef zone at Irene Reef (15-084) in 1994-95 remained near or at outbreaking densities for 5 consecutive years. During this period, Live Hard Coral Cover (LHCC) in this part of the reef declined from a pre-outbreaking level of around 35% live cover to a remnant cover of only around 5% - a reduction of about 85% based on the initial LHCC. Across the entire reef, COTS feeding activity during the outbreak resulted in a loss of some 70% of the initial LHCC (down to around 10% from a pre-outbreaking level of some 32% live cover). Whilst densities of adult COTS in the exposed front reef zone did not reach above sustainable levels during any of our surveys, the observed recent reduction in hard coral cover in this zone is likely to also be the result of COTS feeding activity. It is possible that large numbers of adult COTS were located outside of our predefined depth range of 1-15 meters with only occasional, sporadic incursions of these starfish into shallower water possibly resulting in the loss of live coral cover. Similar short-term incursions could have occurred in between our surveys as a result of active migration by adult starfish from the actively outbreaking back reef zone into the front reef zone.

The outbreaking population of COTS was comprised of multiple cohorts with individual animals ranging in size from 4 to 64 cm in diameter. Distinct peaks in the size-frequency distribution of starfish during the outbreak period suggest that the population contained members of at least seven consecutive cohorts. Recruitment levels of juvenile *A. planci* have remained high since the almost total collapse of the starfish population toward the end of 1999. Recently recruited juvenile starfish (estimated age 1) have now dominated the sample at this reef for the past three seasons since 1998-99 suggesting that Irene Reef has received an ongoing influx of significant numbers of new *A. planci* recruits for at least the last 10 years. Throughout the past 7 years, hard coral cover in the exposed front reef zone has remained at levels suitable to facilitate the growth of juvenile starfish to at least the sub-adult stages. Consequently, it is safe to assume that the small juvenile COTS observed during all recent surveys are members of distinct, consecutive cohorts rather than being non-growing members of previous year classes. As natural mortality rates of small juvenile COTS are likely to be high there is little doubt that members of respective year classes would not survive in any significant numbers over the 12-months period between outbreaks. Whilst it appears unlikely that the lack of suitable prey items will allow these latest cohorts to reach maturity, their potential impact on the process of hard coral recovery remains of some concern. LHCC in the back reef zone has now remained at a low level of around 5% cover for some 4 years with little signs of any significant recovery. In 2000-01, the density of adult COTS in the back reef zone was again low with current numbers of starfish posing little threat to reef recovery in the short-term. Consequently, the back reef zone at Irene Reef continuous to be classified as a Post Spot Outbreak (PSO).

Figure 3.6: Evening Reef (15-095)

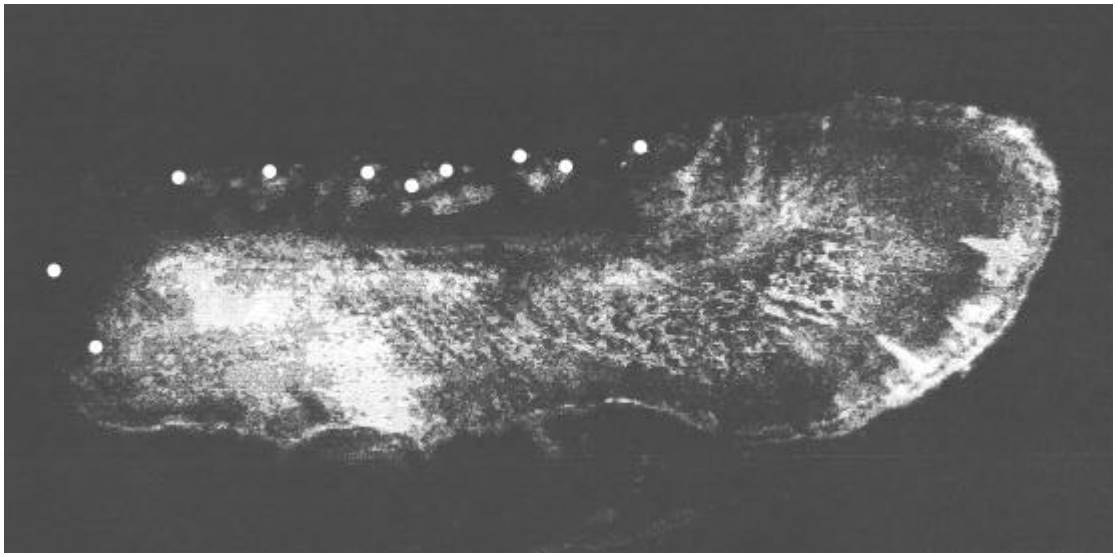


Figure 3.6.1: Aerial photograph of Evening Reef (15-095) with white dots indicating the approximate locations of the 10 sites surveyed in May 2001.

A - Year	1994-95	1995-96	1996-97	1997-98	1998-99	1999-00
Status	ASO(BR) NO(FR)	ASO(BR) ISO(FR)	ASO(BR) NO(FR)	PSO(BR) NO(FR)	PSO(BR) NO(FR)	PSO(BR) ISO(FR)

B – 2000-01 Sample area	Juveniles (est. age 1)	Sub-adults (est. age 2)	Adults (est. age 3 or older)	Status 2000-01
Back Reef (BR)	0.20±0.12 (4)	0.15±0.08 (3)	0.05±0.05 (1)	PSO
Front Reef (FR)	NS	NS	NS	NS
Entire Reef (R = BR & FR)	(4)	(3)	(1)	PSO(BR) NS(FR)

Table 3.6 (A-B): Summary of reef status classifications for Reef 15-095 since 1994-95 (A) and mean densities (±1 S.E.) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 2000-01 (B). Values shown in brackets are total *A. planci* counts.

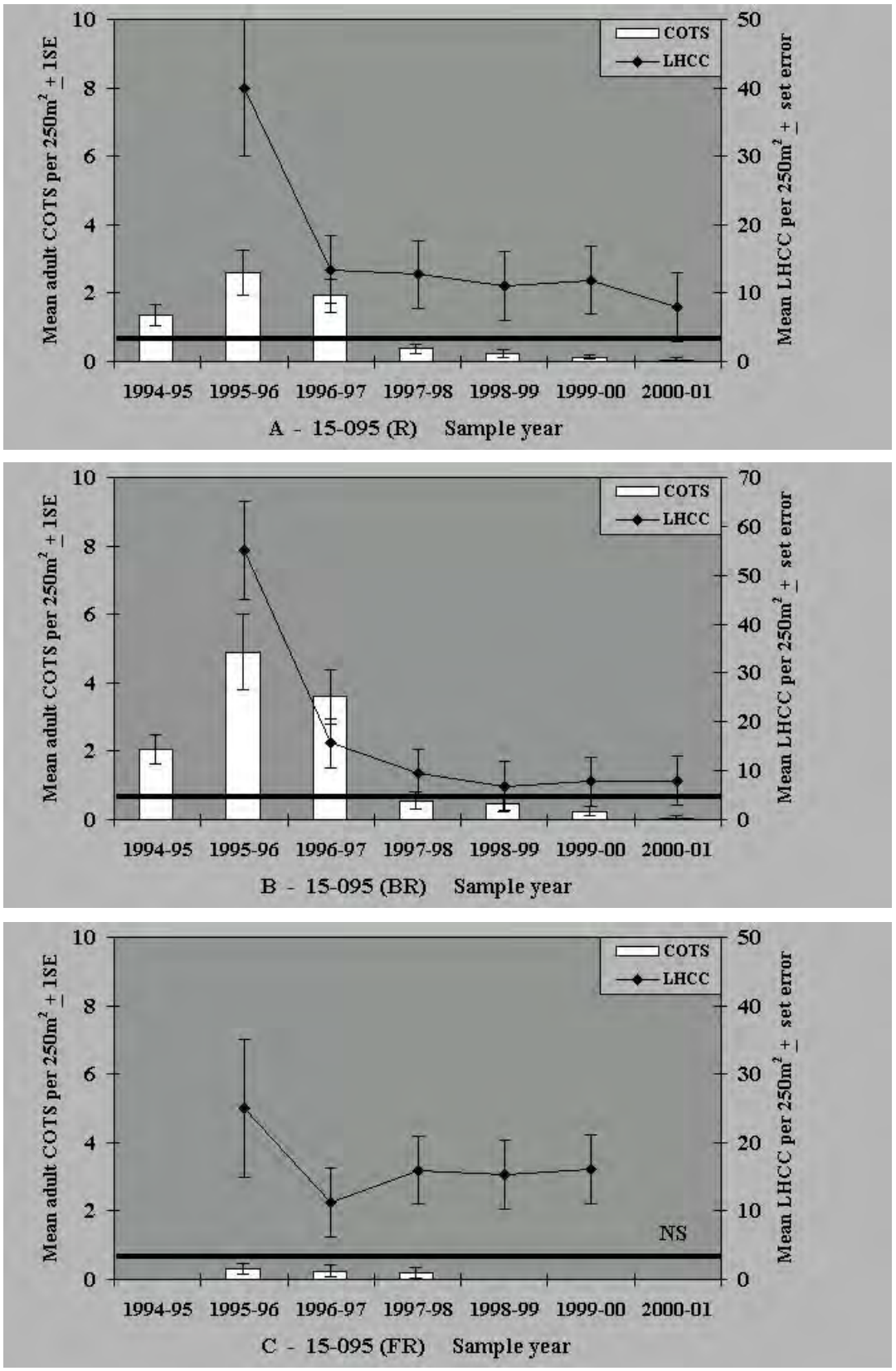


Figure 3.6.2 (A-C): Reef 15-095 - Recent trends in the mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back reef zone (B-BR) and in the front reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbreaking population.

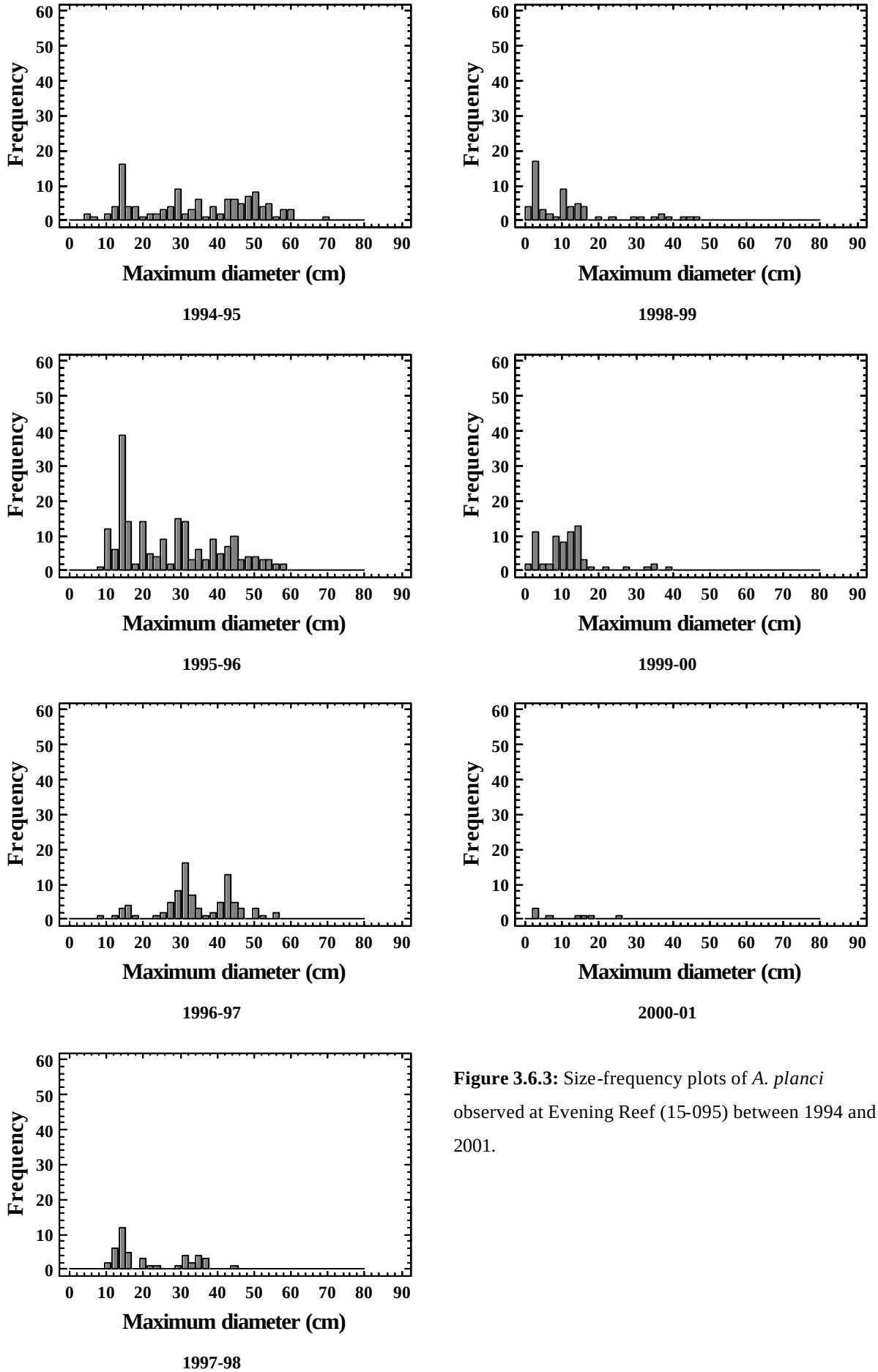


Figure 3.6.3: Size-frequency plots of *A. planci* observed at Evening Reef (15-095) between 1994 and 2001.

Summary

A severe Active Spot Outbreak (ASO) was first discovered in the back reef zone at Evening Reef (15-095) in 1994-95. Outbreaking densities in this part of the reef reached a peak of approximately 6-times sustainable levels with the outbreak persisting for 3 consecutive years until early 1997. During this period, live hard coral cover (LHCC) in the back reef zone declined from around 55% live cover to a remnant cover of just under 10% - a reduction of some 82% from the initial hard coral cover present prior to the outbreak. Live coral cover in the back reef zone has remained at a low level of less than 10% cover since 1997. Across the entire reef, the loss of coral cover due to COTS feeding activity was estimated at 75% with reef-wide LHCC being reduced from an average of approximately 40% live cover down to around 10% cover. Remnant populations of hard corals in the back reef zone are almost exclusively dominated by massive *Porites* spp., the branching coral *Acropora brueggemanni* and isolated stands of *Porites cylindrica*.

The outbreaking population of COTS was comprised of multiple cohorts with individual animals ranging in size from 6 to 70 cm in diameter. Distinct peaks in the size-frequency distribution of starfish suggest that at least 7 consecutive cohorts or year classes contributed to the above-sustainable densities of COTS observed during this period. Since the virtual collapse of the outbreaking population in 1997, recruitment of juvenile starfish has remained at significant levels. Whilst two recently recruited cohorts appear to have failed to reach maturity, their presence may have affected both the onset and magnitude of hard coral recovery. This notion is supported by the fact that local LHCC has failed to show any significant improvement in recent times. However, much reduced numbers of COTS recorded in 2000-01 are unlikely to pose any significant threat to the reef recovery process in the near future.

Whilst densities of adult COTS in the exposed front reef zone did not reach above sustainable levels during any of our surveys, the observed recent reduction in hard coral cover in this zone is likely to also be the result of COTS feeding activity. It is possible that large numbers of adult COTS were located outside of our predefined depth range of 1-15 meters with only occasional, sporadic incursions of these starfish into shallower water possibly resulting in the loss of live coral cover. Similar short-term incursions could have occurred in between our surveys as a result of active migration by adult starfish from the actively outbreaking back reef zone into the front reef zone.

Due to severe and persistent weather conditions experienced in May 2001 we were unable to re-survey the exposed front reef zone of Evening Reef (15-095).

Figure 3.7: Rudder Reef (16-023)

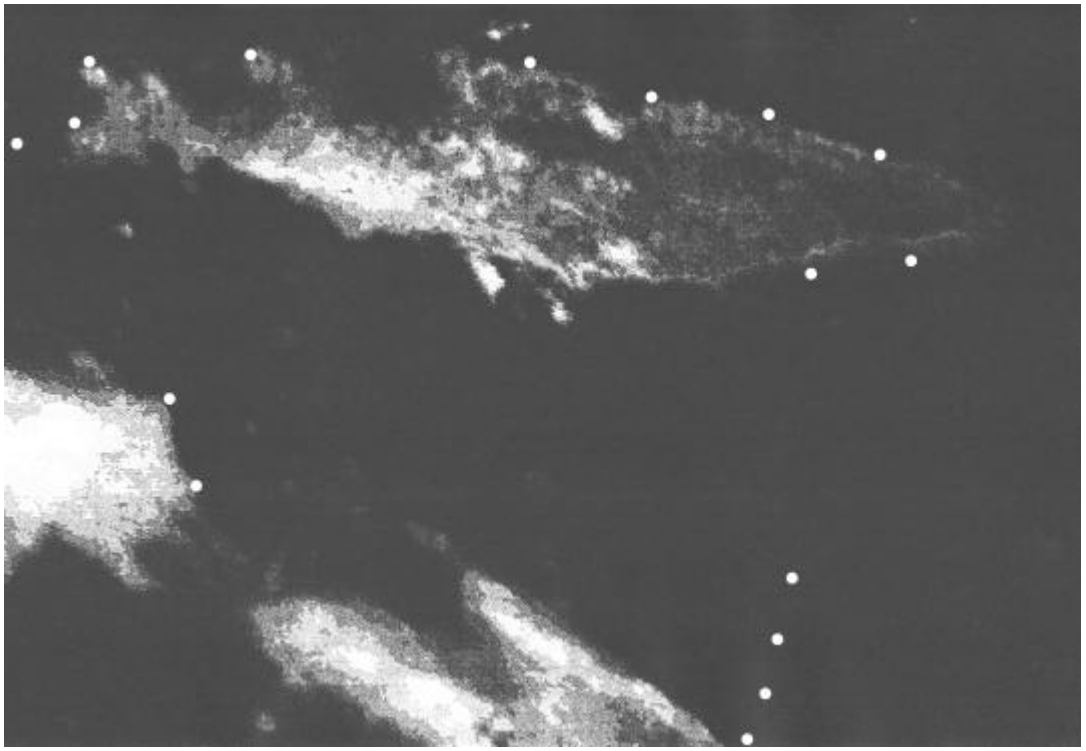


Figure 3.7.1: Aerial photograph of Rudder Reef (east) (16-023) with white dots indicating the approximate locations of 16 sites surveyed in March and May 2001. Note that four of the front reef sites surveyed were located outside the image to the south of the area shown.

A - Year	1994-95	1995-96	1996-97	1997-98	1998-99	1999-00
Status	NO	IO	AO	ASO(BR) PSO(FR)	ASO(BR) FSO(FR)	PSO(BR) ISO(FR)

B – 2000-01 Sample area	Juveniles (est. age 1)	Sub-adults (est. age 2)	Adults (est. age 3 or older)	Status 2000-01
Back Reef (BR)	0.40±0.22 (8)	0.05±0.05 (1)	0.00±0.00 (0)	PSO
Front Reef (FR)	0.85±0.32 (17)	0.00±0.00 (0)	0.10±0.07 (2)	PSO
Entire Reef (R = BR & FR)	0.63±0.20 (25)	0.03±0.03 (1)	0.05±0.04 (2)	PO

Table 3.7 (A-B): Summary of reef status classifications for Reef 16-023 since 1994-95 (A) and mean densities (±1 S.E.) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 2000-01 (B). Values shown in brackets are total *A. planci* counts.

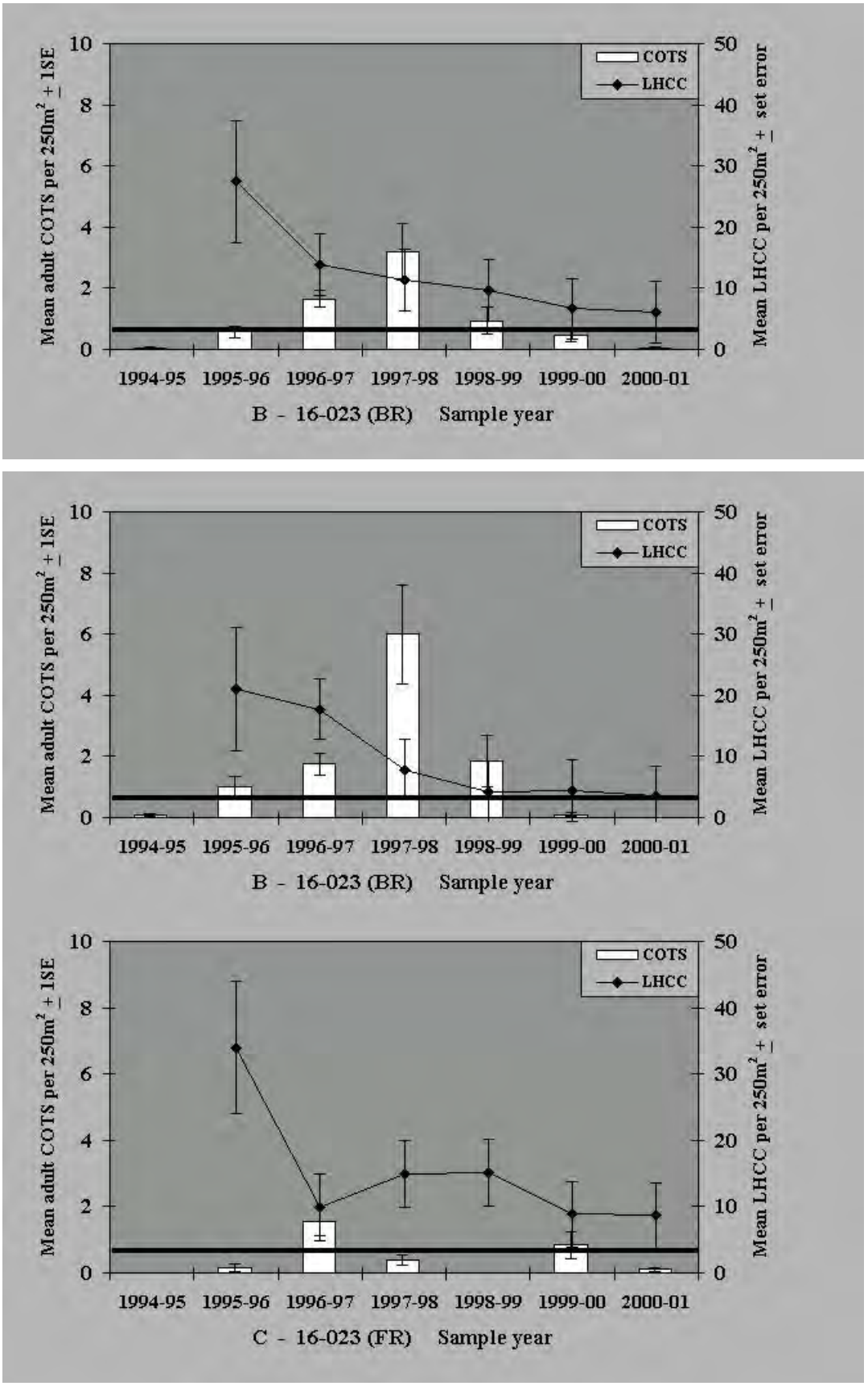


Figure 3.7.2 (A-C): Reef 16-023 - Recent trends in the mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back reef zone (B-BR) and in the front reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbreaking population.

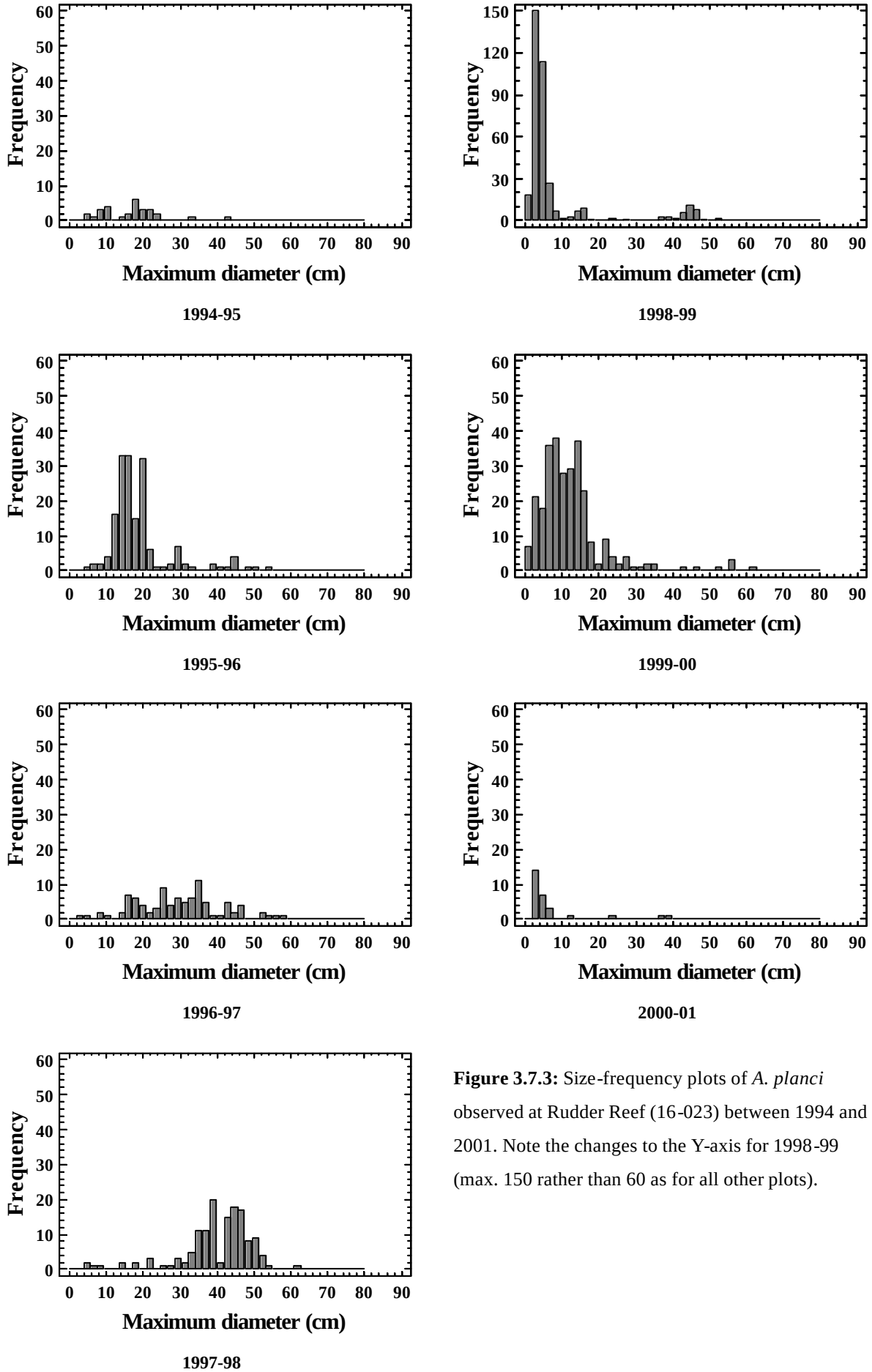


Figure 3.7.3: Size-frequency plots of *A. planci* observed at Rudder Reef (16-023) between 1994 and 2001. Note the changes to the Y-axis for 1998-99 (max. 150 rather than 60 as for all other plots).

Summary

Rudder Reef (16-023) was classified as a reef-wide Incipient Outbreak (IO) in 1995-96. A severe Active Outbreak (AO) had developed by 1996-97, with COTS densities in the back reef zone remaining at above sustainable densities for 3 consecutive years. COTS densities peaked at levels of approximately 8-times sustainable levels. In contrast, the outbreak at the exposed front reef zone was less severe and relatively short-lived with adult starfish densities peaking at around 4.5-times sustainable levels and going back down to sustainable levels within 12 months.

The outbreaking population of COTS was comprised of multiple year classes with individual animals ranging in size from 4 to 62 cm in diameter. Size-frequency distributions recorded during this period suggest that at least 5 consecutive cohorts or year classes were present within the population. Levels of *A. planci* recruitment remained high for two years following the collapse of the initial outbreaking population. However, the large 1997-98 cohort apparently failed to reach maturity, a fact likely to be explained by a lack of suitable hard coral prey. It appears that the remnant cover of around 10% live hard coral in the exposed front reef zone (where most of the juvenile COTS had been located in 1998-99) was insufficient to allow for further starfish growth.

During the outbreak episode, live hard coral cover (LHCC) across the reef declined from an average of around 30% cover to its current level of around 5% live cover – a reduction of approximately 83% from the initial coral cover prior to the outbreak. LHCC in the back reef zone has now been recorded at levels of less than 10% cover for four consecutive years.

The exposed front reef zone recently experienced two separate events where COTS densities were above or near outbreaking levels. The Active Spot Outbreak (ASO) recorded in 1996-97 led to a reduction of LHCC in this zone from average levels of around 35% live cover down to a remnant cover of only 10%. LHCC marginally increased up to around 15% cover over the following two years before a renewed increase in the number of adult COTS again caused another decline in LHCC – this time from 15% down to 10% cover. It appears likely that the low LHCC in this reef zone was responsible for the virtual disappearance of sub-adult and adult COTS over the past twelve months. Numbers of starfish recorded in 2000-01 in both reef zones are unlikely to have any significant effect on the reef recovery process in the near future. Rudder Reef (16-023) has been classified as Post-Outbreaking (PO).

Figure 3.8: Unnamed Reef (16-024)

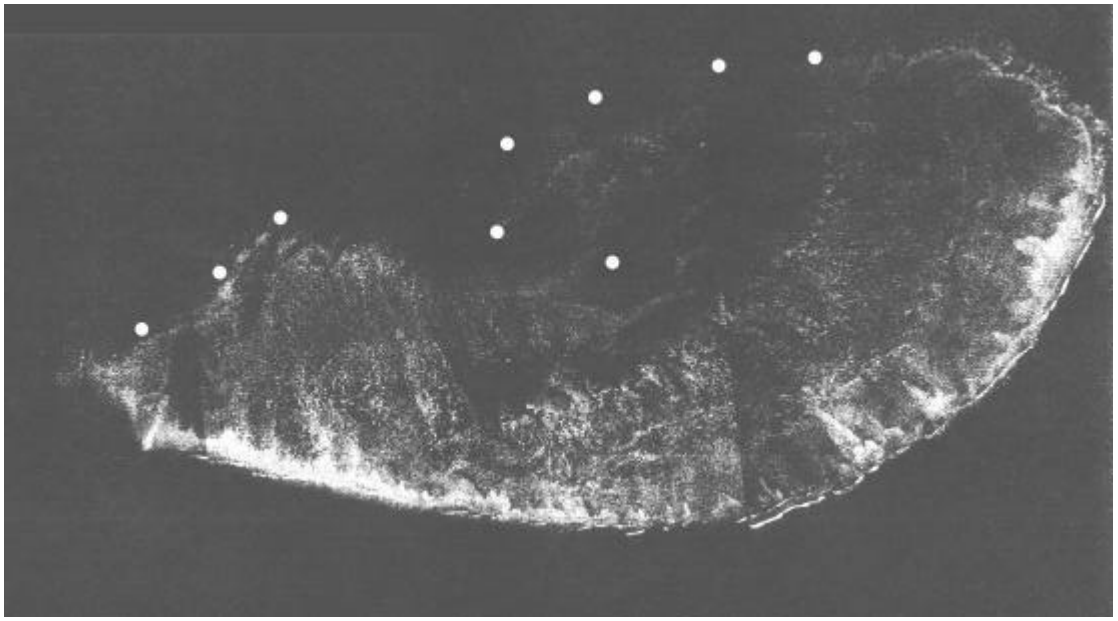


Figure 3.8.1: Aerial photograph of Unnamed Reef (16-024) with white dots indicating the approximate locations of the 10 sites surveyed in March 2001.

A - Year	1994-95	1995-96	1996-97	1997-98	1998-99	1999-00
Status	NO	IO	AO	AO	PSO(BR) FSO(FR)	PO

B – 2000-01 Sample area	Juveniles (est. age 1)	Sub-adults (est. age 2)	Adults (est. age 3 or older)	Status 2000-01
Back Reef (BR)	0.15±0.15 (3)	0.00±0.00 (0)	0.00±0.00 (0)	PSO
Front Reef (FR)	NS	NS	NS	NS
Entire Reef (R = BR & FR)	(3)	(0)	(0)	PSO(BR) NS(FR)

Table 3.8 (A-B): Summary of reef status classifications for Reef 16-024 since 1994-95 (A) and mean densities (±1 S.E.) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 2000-01 (B). Values shown in brackets are total *A. planci* counts.

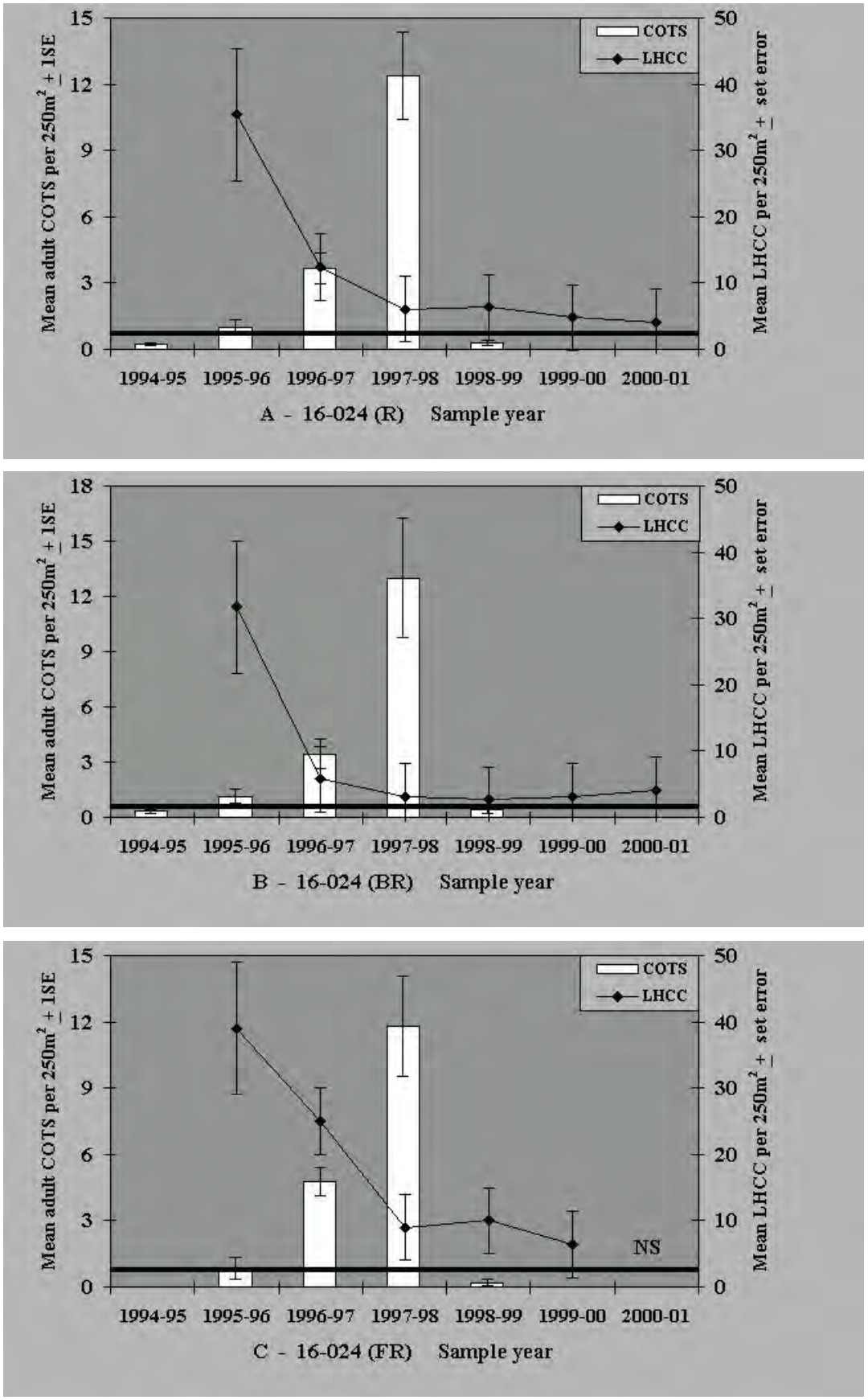
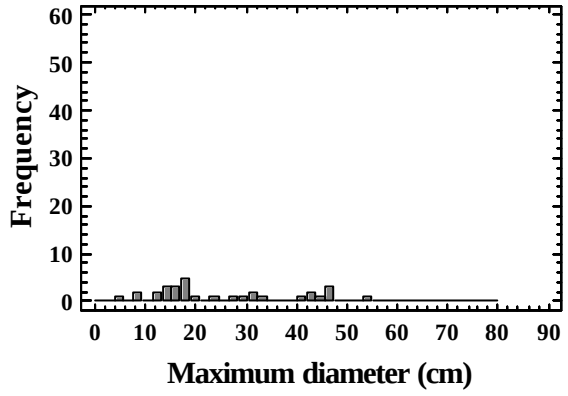
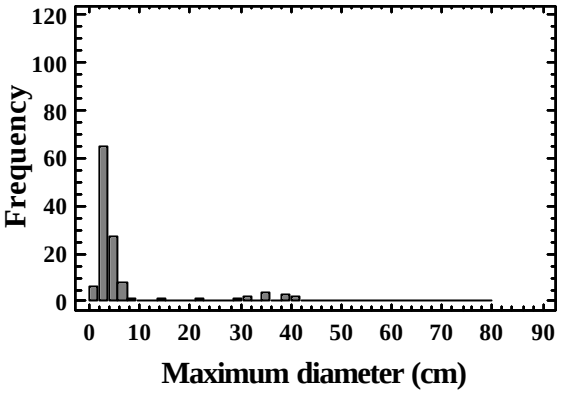


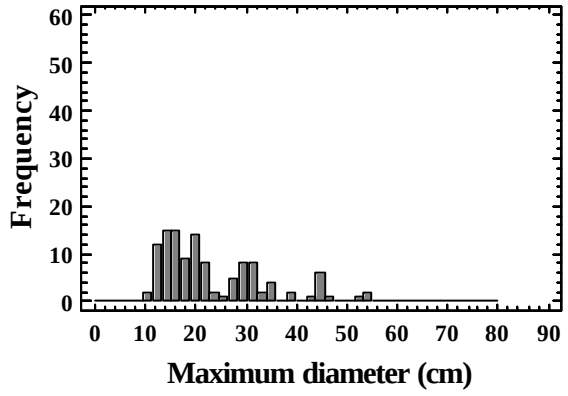
Figure 3.8.2 (A-C): Reef 16-024 - Recent trends in the mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back reef zone (B-BR) and in the front reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbreaking population.



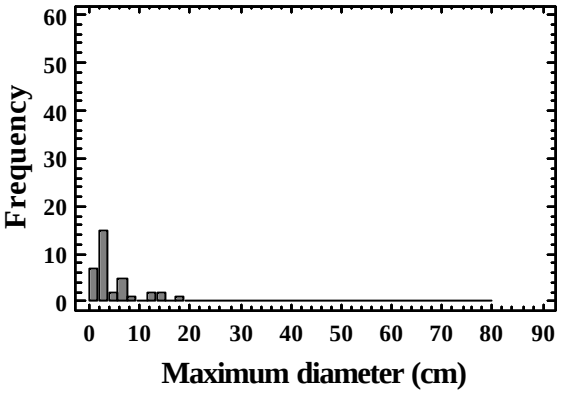
1994-95



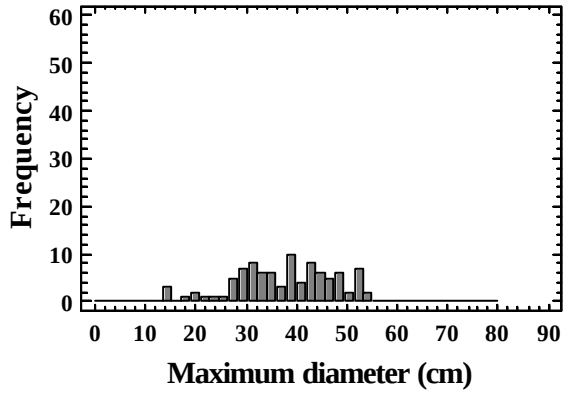
1998-99



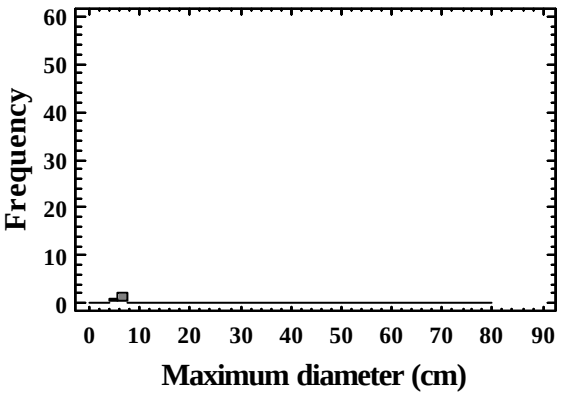
1995-96



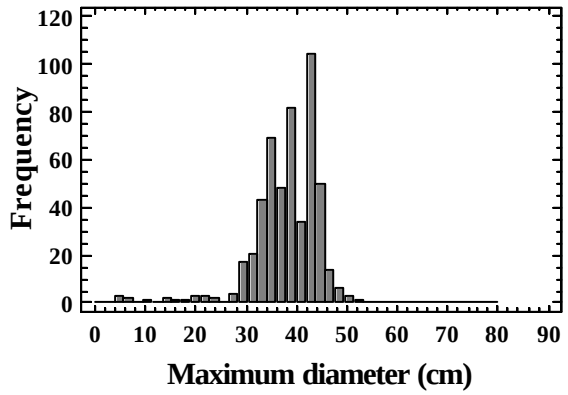
1999-00



1996-97



2000-01 (NB. back reef zone only!)



1997-98

Figure 3.8.3: Size-frequency plots of *A. planci* observed at Unnamed Reef (16-024) between 1994 and 2001. Note the changes to the Y-axis for 1997-98 and 1998-99 (max. of 120 rather than 60 as for all other plots).

Summary

Unnamed Reef (16-024) was classified as an Incipient Outbreak (IO) in 1995-96. A severe Active Outbreak (AO) developed over the following 12 months, with adult starfish populations in both the back and front reef zone remaining at outbreaking densities for two consecutive years. At the outbreak's peak in 1997-98 adult densities across the reef were recorded at approximately 16-times sustainable levels. During this period, live hard coral cover (LHCC) across the reef declined from an average of around 35% cover down to approximately 5% live coral cover – a reduction in LHCC of some 85% from the initial cover prior to the outbreak.

Interestingly, the extremely high density of individuals in the 30-50 cm size range was sustained over two consecutive years. The apparently quite stable size-frequency distribution observed over this size range may be explained by extreme levels of food limitation. As the density of starfish in this size range was amongst the highest recorded anywhere over the seven sampling period of the fine-scale surveys, we suggest that resource (food) limitation may have resulted in an inability of individual starfish to achieve further growth.

The outbreaking population of starfish was comprised of multiple cohorts with individual animals ranging in size from 6 to 54 cm in diameter. Size-frequency distributions recorded during the outbreak episode suggest that at least 4 consecutive cohorts or year classes contributed to the above-sustainable numbers of starfish.

Coral cover in the back reef zone remains at very low levels of around 5% live cover. Since the 1996-97 survey, LHCC has now been recorded at levels of around 5% for five consecutive years with few significant signs of recovery being observed. The number of COTS recorded in this zone (3 individuals) was the lowest recorded since the inception of the fine-scale surveys in 1994-95. Due to the virtual absence of COTS from this reef zone there appears to be little threat to the process of reef recovery in the short term.

Due to severe and persistent weather conditions experienced in March 2001 we were unable to re-survey the exposed front reef zone of Unnamed Reef 16-024.

Figure 3.9: Thetford Reef (16-068)

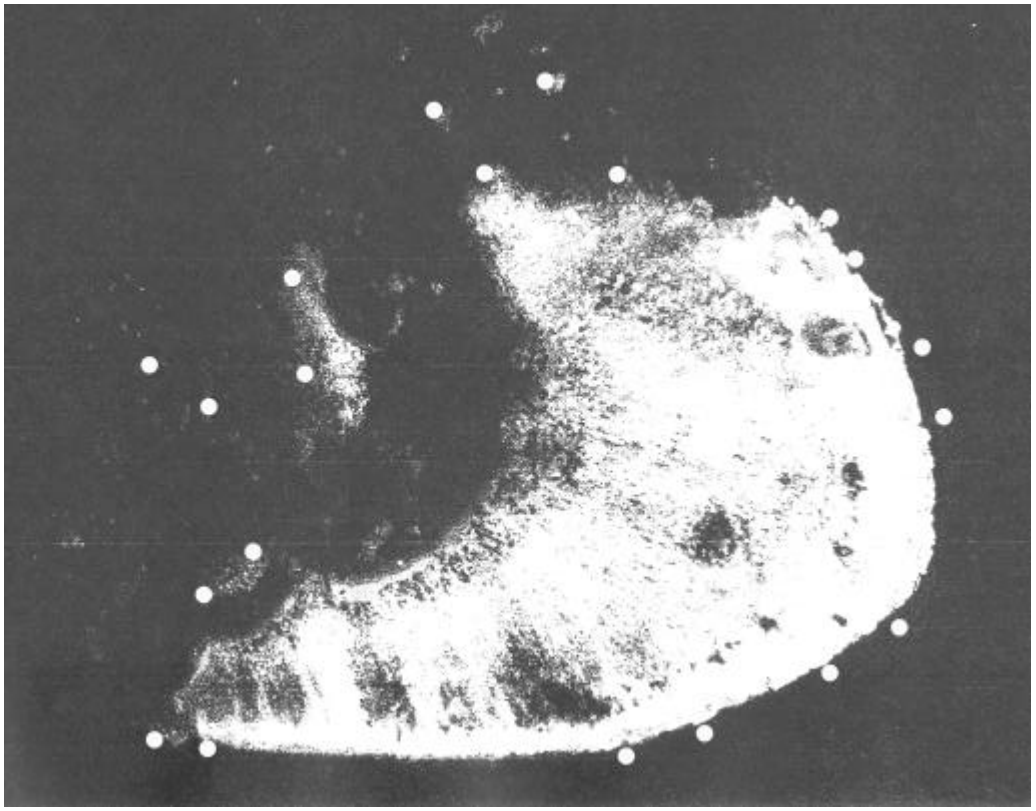


Figure 3.9.1: Aerial photograph of Thetford Reef (16-068) with white dots indicating the approximate locations of the 20 sites surveyed in April 2001.

A - Year	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Status	NO	NO	ASO(BR) NS(FR)	PSO(BR) NO(FR)	PSO(BR) FSO(FR)	ISO(BR) ASO(FR)

B – 2000-01 **Sample area**	**Juveniles** **(est. age 1)**	**Sub-adults** **(est. age 2)**	**Adults (est.** **age 3 or older)**	**Status** **2000-01**
Back Reef **(BR)**	0.05±0.05 (1)	0.10±0.07 (2)	0.85±0.30 (17)	PSO
Front Reef **(FR)**	0.05±0.05 (1)	0.70±0.25 (14)	5.05±1.42 (101)	ASO
Entire Reef **(R = BR & FR)**	0.05±0.03 (2)	0.40±0.14 (16)	2.95±0.79 (118)	PSO(BR) ASO(FR)

Table 3.9 (A-B): Summary of reef status classifications for Reef 16-068 since 1994-95 (A) and mean densities (±1 S.E.) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 2000-01 (B). Values shown in brackets are total *A. planci* counts.

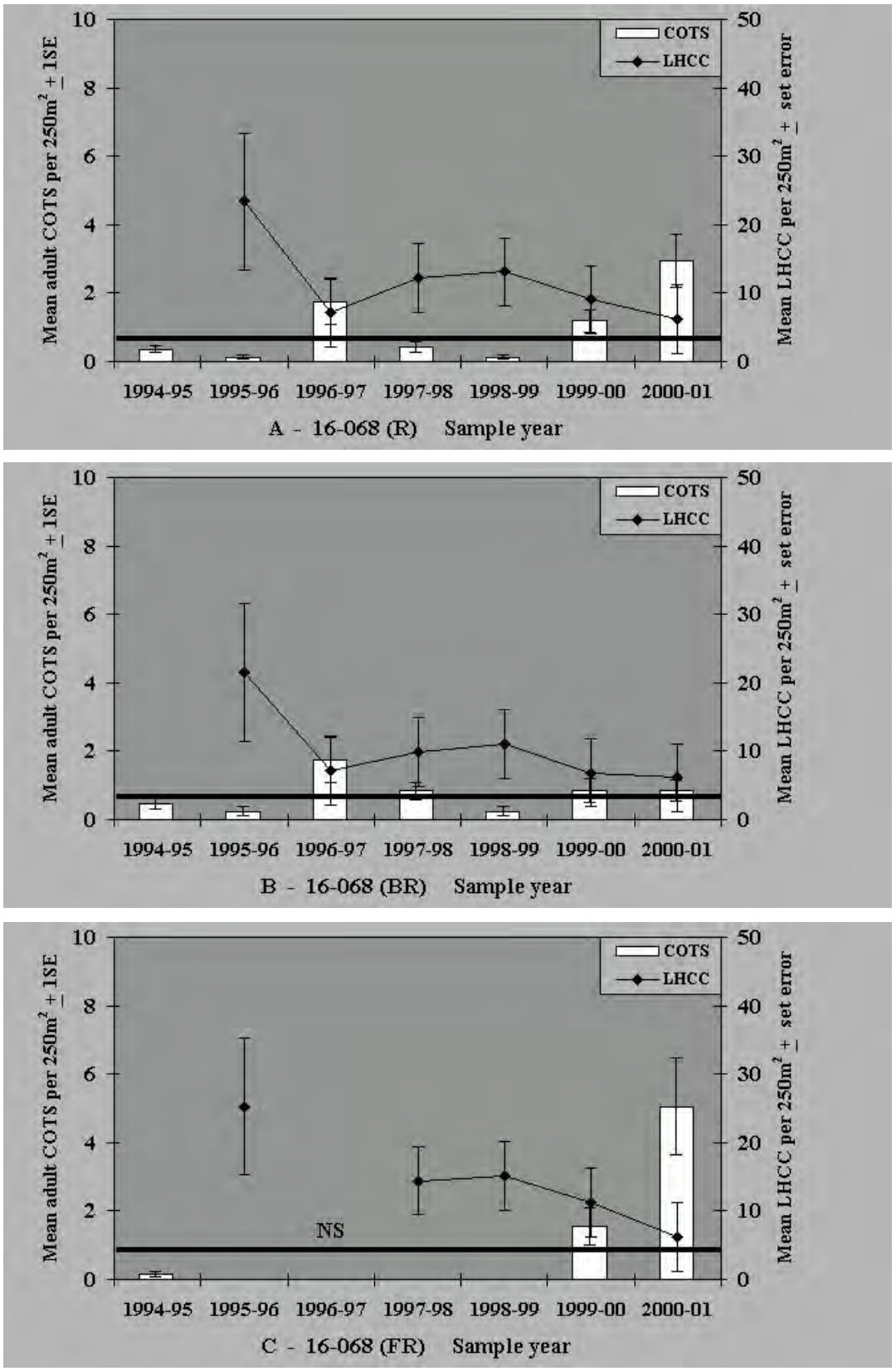
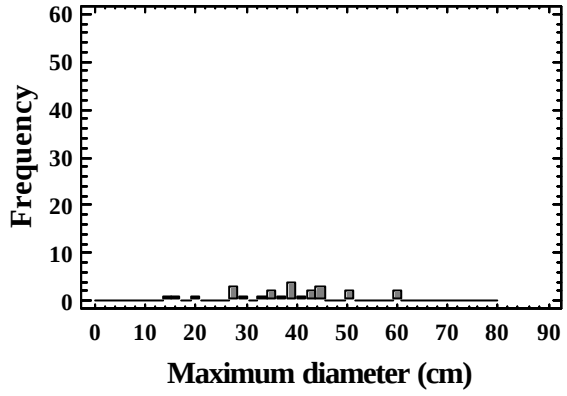
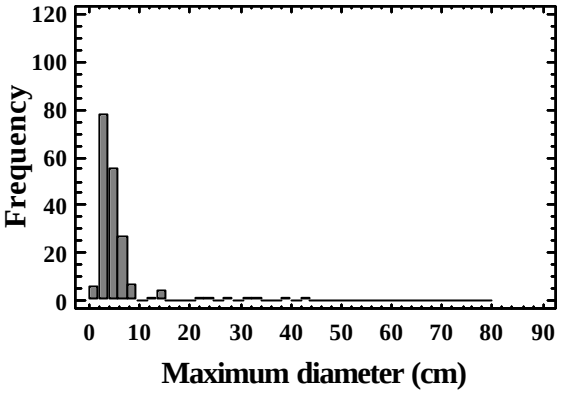


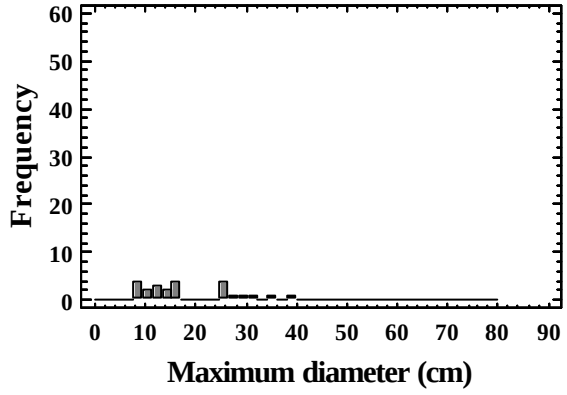
Figure 3.9.2 (A-C): Reef 16-068 - Recent trends in the mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back reef zone (B-BR) and in the front reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbreaking population.



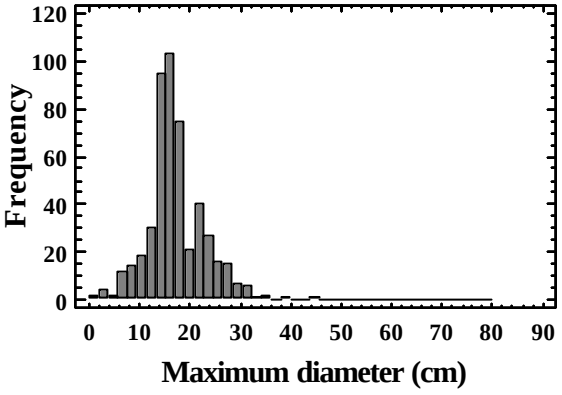
1994-95



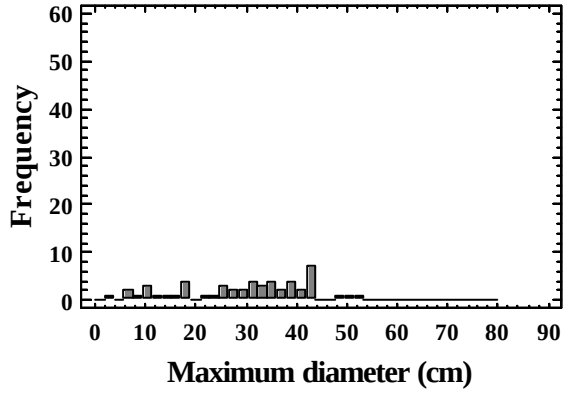
1998-99



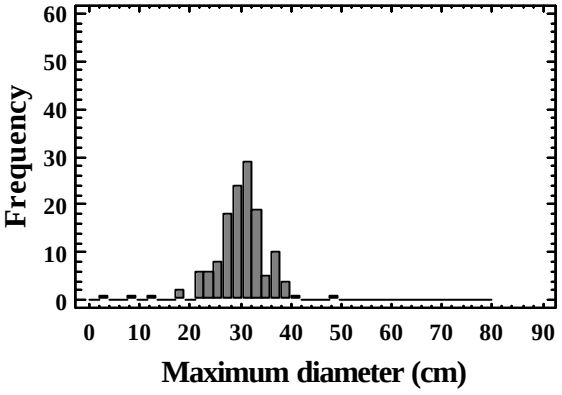
1995-96



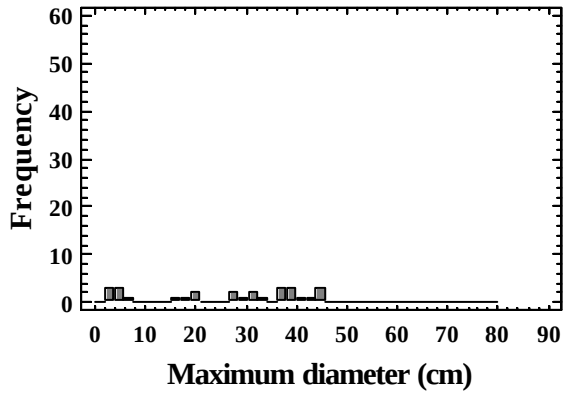
1999-00



1996-97



2000-01



1997-98

Figure 3.9.3: Size-frequency plots of *A. planci* observed at Thetford Reef (16-068) between 1994 and 2001. Note the changes to the Y-axis for 1998-99 and 1999-00 (max. of 120 rather than 60 as for all other plots).

Summary

The first signs of unsustainable *A. planci* densities at Thetford Reef (16-068) were first detected in 1996-97. The Active Spot Outbreak (ASO) identified in the back reef zone that year resulted in a reduction of live hard coral cover (LHCC) from pre-outbreaking levels of around 20% down to low levels of less than 10% live cover. A reduction in the number of starfish in this zone over the following two years resulted in a corresponding marginal increase of LHCC back up to around 10-15% live cover. However, renewed starfish population increases observed in 1999-00 again resulted in a significant loss of LHCC down to the current very low level of around 5% live cover. Densities of adult COTS in the back reef zone have remained at near outbreaking levels for the past two years. The back reef zone of Thetford Reef has now experienced two significant COTS feeding events in the past four years with LHCC suffering significant losses on each occasion.

It is highly likely that recent COTS control programs undertaken by local reef tourism companies in the protected back reef zone of Thetford Reef have resulted in a significant reduction of adult starfish density. Consequently, the estimated adult starfish density is almost certainly significantly lower than it would have been in the absence of such control measures. The Active Spot Outbreak (ASO) predicted following the 1999-00 surveys almost certainly eventuated prior to the 2000-01 survey. However, the remnant population of adult COTS still present in April 2001 was recorded at just below the threshold for a classification as an active spot outbreak.

The exposed front reef zone has shown very similar recent trends for both COTS and coral populations. The most recent outbreak episode affecting this zone was first recorded in 1999-00 but has persisted since that time. In line with predictions made following the completion of the 1999-00 survey, the density of adult COTS in this zone has further increased leading to a corresponding reduction in LHCC down to a remnant level of only 5% cover. Over the past 5-6 years, the exposed front reef zone has experienced an overall loss of LHCC from an average of around 25% down to a remnant cover of 5% - a loss of some 80% of the initial coral cover prior to recent outbreak activity.

3.3 Recent trends in reef status classifications

Active Outbreaks (ASO/AO): The overall percentage of core survey reefs with active spot or reef-wide outbreaks in 2000-01 was recorded at 11% (1/9 reefs) which is approximately $1/10^{th}$ of the 100% figure recorded across the survey area during the most recent peak in outbreak activity in 1996-97 (Fig. 4a).

Incipient Outbreaks (ISO/IO): The 2000-01 surveys did not record any incipient spot and/or reef-wide outbreaks (Fig. 4b).

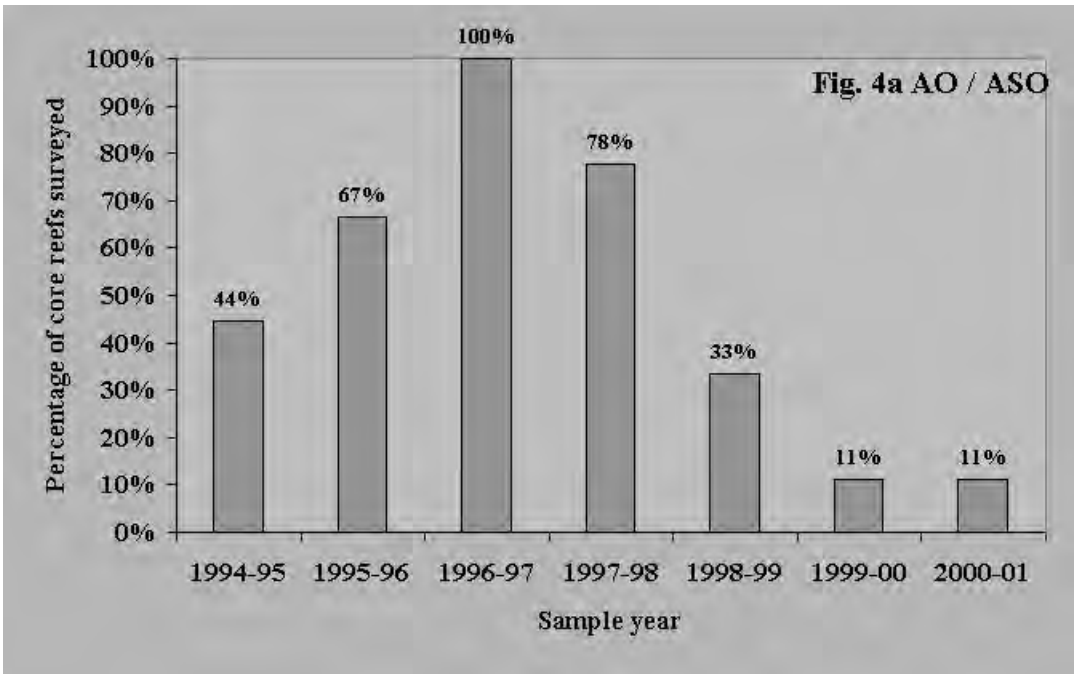
Post outbreaking reefs (PSO/PO): The percentage of post-outbreaking reefs in the survey area was estimated at 89%, which represents a substantial increase from the 22% estimated in 1999-00 (Fig. 4c).

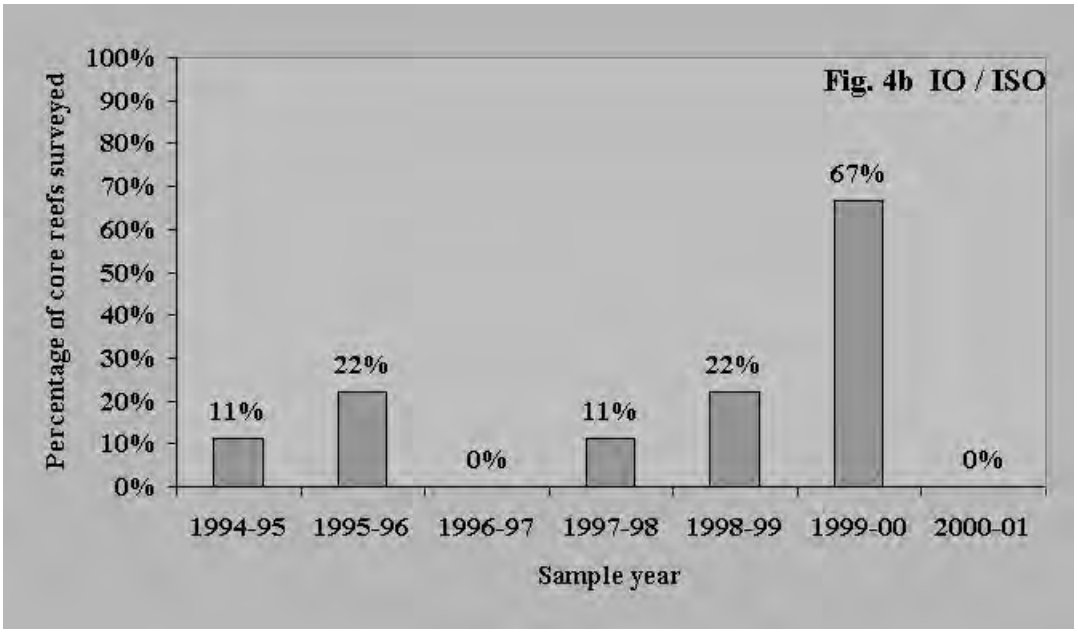
Non-outbreaking reefs (NSO/NO): The percentage of unaffected, non-outbreaking reefs within the core set of 9 reefs surveyed every year since 1994-95 declined to 0% during the peak in regional outbreak activity in 1996-97 (Fig. 4d). Our findings suggest that 100% of mid-shelf reefs located within the survey area have been affected by recent starfish outbreaks.

Table 4: Summary counts of respective reef classification categories as assigned to individual core survey reefs since 1994-95 *(sub-set of nine reefs surveyed every year: Reefs 14-132b, 15-019, 15-024, 15-070, 15-084, 15-095, 16-023, 16-024, and 16-068).*

Reef status	***Status 1994-95***	***Status 1995-96***	***Status 1996-97***	***Status 1997-98***	***Status 1998-99***	***Status 1999-00***	***Status 2000-01***
# reefs	**9**	**9**	**9**	**9**	**9**	**9**	**9**
AO / ASO	4	6	9	7	3	1	1
IO / ISO	1	2	0	1	2	6	0
PO / PSO	0	0	0	1	4	2	8
NO / NSO	4	1	0	0	0	0	0

Figure 4: Bar charts of observed annual trends in the percentage of core survey reefs classified as (**4a**) actively outbreaking (ASO/AO), (**4b**) incipient outbreaks (ISO/IO), (**4c**) post-outbreaking (PSO/PO) and (**4d**) non-outbreaking (NSO/NO).
(Analysis based on sub-set of nine reefs surveyed every year since 1994-95: Reefs 14-132b, 15-019, 15-024, 15-070, 15-084, 15-095, 16-023, 16-024, and 16-068).





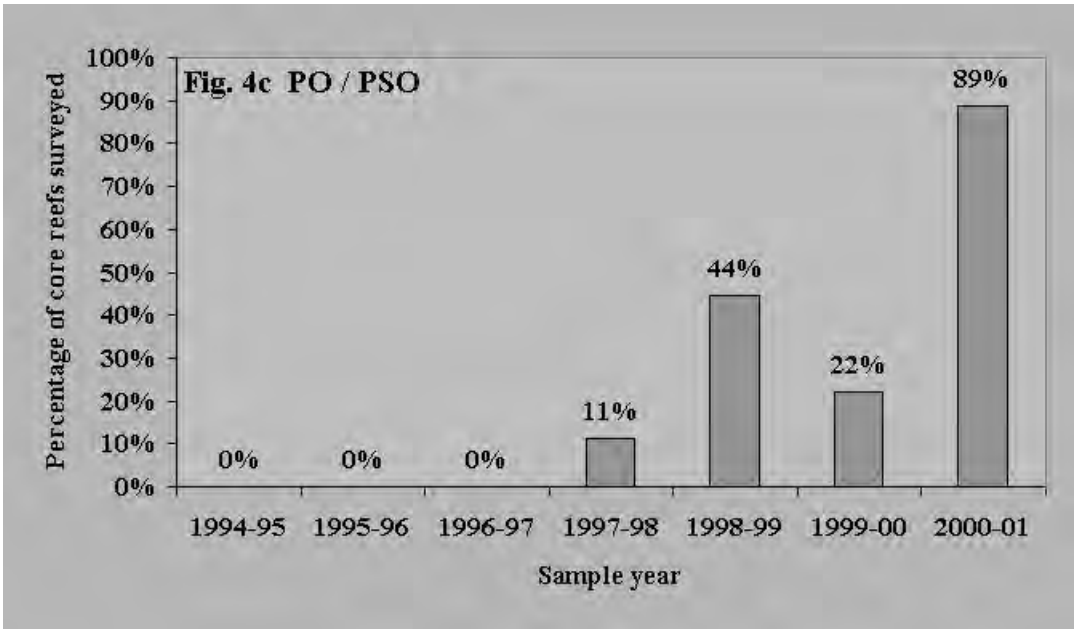


Fig. 4c PO / PSO
Percentage of core reefs surveyed
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0%
0%
0%
11%
44%
22%
89%
1994-95
1995-96
1996-97
1997-98
1998-99
1999-00
2000-01
Sample year

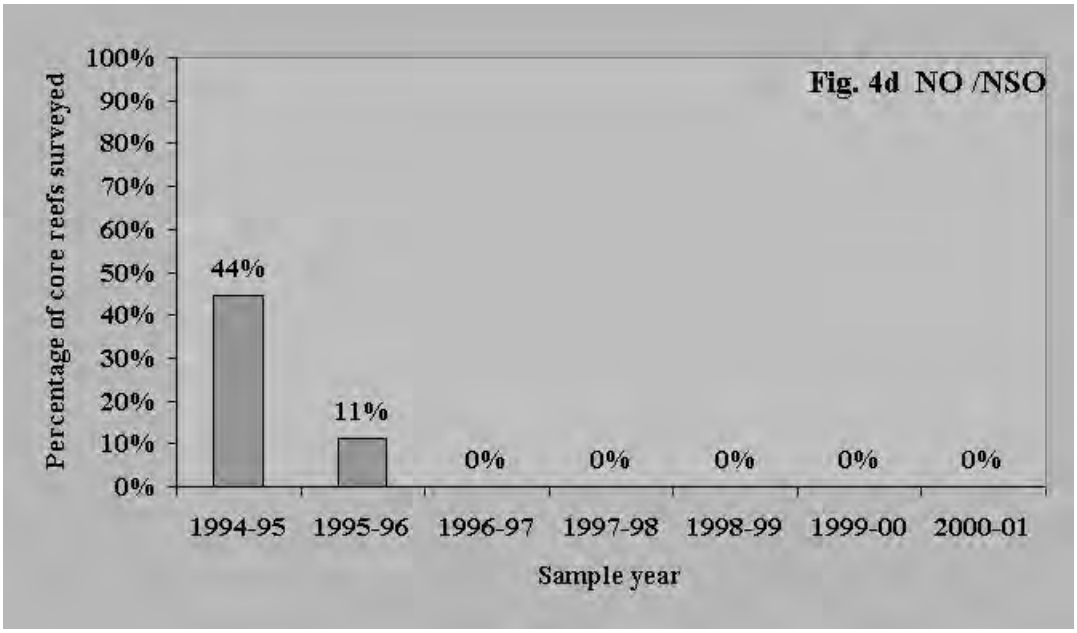


Fig. 4d NO /NSO
Percentage of core reefs surveyed
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
44%
11%
0%
0%
0%
0%
0%
1994-95
1995-96
1996-97
1997-98
1998-99
1999-00
2000-01
Sample year

4. DISCUSSION

Effects of outbreaks

All nine core reefs surveyed annually since 1994-95 have experienced active spot and/or reef-wide COTS outbreaks over the past 7 years. Generally, these outbreaks have been severe with starfish feeding activity resulting in average, reef-wide losses of hard coral cover ranging from approximately 66% (at Unnamed Reef 15-070) to 89% (at Rocky Islets Reef b) of the initial live coral cover present prior to the outbreaks. Remnant live hard coral cover averaged across these reefs ranges from a very low 5% live cover to a maximum of around 10-15% cover. Remnant populations of hard coral are generally characterised by a small number of species that appear to be *A. planci's* least preferred prey items. They include the massive forms of the Genus *Porites*, the branching corals *Porites cyclindrica* and *P. nigrescens* as well as a variety of favid corals including the Genus *Diploastrea*.

Given that all fine-scale survey reefs were initially chosen at random and hence are deemed to be representative of the survey area, our results are suggesting that live hard coral on virtually 100% of mid-shelf reefs in this part of the central GBR region has been affected by the latest outbreak episode. Personal observations and additional detailed reports received from Reef-users also suggest that a significant number of outer and inner shelf reefs in the central GBR region are being affected by current starfish activity. Some of these reports have confirmed current outbreak activity in parts of the reef that were apparently unaffected during the last outbreak episode during the 1980's (various reef tourism operators, *pers. com.*).

The strong 1997-98 cohort of *A. planci*, first observed during the 1998-99 surveys season, has had varied impacts across the set of nine core reefs. In 1999-00, all nine reefs supported significant densities of sub-adult starfish leading to local classifications of renewed Incipient Outbreaks (IO). However, in all but one case, it appears that remnant coral cover of only 5-10%, as recently recorded on these reefs, was insufficient to allow for further growth and maturation of this cohort. The only survey reef seriously affected by the 1997-98 cohort was Thetford Reef (16-068) where the available hard coral cover was recorded at around 15% live cover – apparently a sufficiently large source of suitable prey items to allow for starfish maturation and the development of a renewed outbreak.

Whilst the 1997-98 cohort of starfish has largely failed to reach maturity, there are indications that it may have had a significant effect on the onset and magnitude of the recovery process on COTS-affected reefs. Personal observations made in recent years suggest a strong preference by small juvenile COTS for feeding on recently recruited hard corals. It appears highly likely that these preferences have resulted in significant losses to local coral populations dominated by small remnant as well as newly settled corals. However, the fact that the numbers of juvenile COTS observed across the survey area in 2000-01 has dropped from the previous high levels suggests that rates of local hard coral recovery may increase in the near future as the feeding pressure is further reduced.

Population characteristics

Outbreaking populations of *A. planci* across the nine core reefs have been characterised by the presence of multiple cohorts or year classes with size-frequency distributions of starfish indicating that between four and seven consecutive year classes ('pseudo-cohorts') were combining to cause the severe recent outbreaks in this region. Furthermore, levels of *A. planci* recruitment have continued to be significant with most survey reefs having received ongoing recruitment even after the collapse of the initial outbreaking populations. In some cases, for example at Irene Reef (15-084), our data suggest that significant numbers of starfish have successfully recruited to the reef over a period of at least ten years.

The observed pattern of recruitment also suggests that COTS outbreaks, at least in this part of the Great Barrier Reef, are not the result of a single unusual event that causes a once off, yet highly successful recruitment pulse. Rather, it would appear that the observed outbreaks are the result of relatively persistent environmental factors and conditions favouring *A. planci's* recruitment success synchronously across a geographic area spanning several degrees of latitude. Consequently, it appears highly unlikely that a single, sporadic event, such as a major river run-off and subsequent flood plume, could have provided a trigger for the recent outbreak episode. Based on our results, it would appear far more likely that chronic and persistent factors may be responsible for the high levels of ongoing recruitment success.

The strongly size-specific patterns of within-reef distribution of juvenile and sub-adult starfish that were positively identified in 1998-99 (see Engelhardt *et al.* 2000) and again in 1999-00 (see Engelhardt *et. al.* 2001) have important implications for future monitoring of *A. planci*

populations. If the main objective is the early detection of developing outbreaks (*forecasting capability*), then it would appear that considerable effort should go into sampling

reef front environments. In contrast, if the main objective is an assessment of past recruitment events on reefs (*hindcasting capability*), then both back and front reef zones may have to be surveyed in order to gain a complete insight into the probable age structures of local starfish populations.

Conclusions and recommendations

Based on our observations over the past 7 years, we suggest that our understanding of the ultimate cause(s) of the observed outbreaks would greatly benefit from the continuation of dedicated fine-scale monitoring of COTS with the aim of further investigating the dynamics of *A. planci's* populations in this critically important area of the GBR Marine Park. With regard to the need for ongoing monitoring, the period between successive outbreak episodes may be of particular importance. At this stage, our understanding of the population structure and dynamics of *A. planci* during the inter-outbreak period is extremely sketchy. Detailed records on starfish abundance and size-frequency distributions within local and regional populations appear to offer the only realistic chance of improving our understanding of this critically important phenomenon.

As outbreaks of COTS have been shown to be the single-most important source of coral mortality in the Great Barrier Reef World Heritage Area, those responsible for the continued and sustainable management of this critical area should feel obliged to intensify their efforts at trying to more fully understand the relative importance of natural versus human factors in the ultimate causation of the outbreak phenomenon. This is particularly important as repeated outbreak episodes in this part of the Great Barrier Reef may in fact lead to a long-term, step-wise degradation of reefs where coral cover is unable to fully recover between successive outbreak events.

Many of the recently observed populations of small juvenile starfish have failed to develop and mature to adulthood on what were already severely COTS-affected reefs. A lack of a suitable quantity of their hard coral food provides the likely explanation for the observed pattern. However, the fact that COTS settlement and initial recruitment success in at least part of the study area remains high should be treated with some concern as frequent or chronic outbreaks

of *A. planci* could result in permanently degraded reef sites unable to recover from repeated high-level disturbances, a scenario with serious implications for the future operations and sustainability of the regional Reef tourism industry. Strategic efforts aimed at assessing possible indications of such detrimental trends and conditions should be given the highest priority.

Intensive fine-scale monitoring of *A. planci* and associated live hard coral cover should be continued to maximise the chances of (a) detecting the early signs of renewed COTS activity, (b) identifying possible signs of further reef degradation and reduced coral recovery rates and (c) improving our understanding of outbreak causality.

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APPENDIX A

Overviews and summaries of individual survey reefs and their respective classifications with regard to outbreaks of *A. planci*.

Table 5: Overview of the respective status of individual reefs surveyed since 1994-95 using the *A. planci* fine-scale survey methodology.
(*NB: Only reefs surveyed with funding from the CRC Reef Research Centre (CRC Reef) and the Great Barrier Reef Marine Park Authority (GBRMPA) as part of CRC Reef Task 1.6.1 are shown. Reasons for the deletion or addition of individual survey reefs from the annual sampling program are also stated).*

GBR Reef ID	***Reef Name***	***Status 1994-95***	***Status 1995-96***	***Status 1996-97***	***Status 1997-98***	***Status 1998-99***	***Status 1999-00***	***Status 2000-01***
14-116	Lizard Island Reef [1]	AO	NS	NS	NS	NS	NS	NS
14-143	Nth. Direction Reef [1]	ASO(BR) ISO(FR)	AO	AO	NS	NS	NS	NS
14-132b	Rocky Islets Reef (b)	IO	AO	AO	AO	PO	PO	PO
14-133	U/N [2]	IO	AO	NS	AO	NS	NS	NS
15-019	Long Reef	ASO(BR) NSO(FR)	AO	AO	ASO(BR) PSO(FR)	IO	IO	PO
15-024	Mackay Reefs	ASO(BR) NSO(FR)	AO	AO	AO	ASO(BR) PSO(FR)	IO	PO
15-033	Lark Reef (E) [5]	NO	ASO(BR) ISO(FR)	ASO(BR) NSO(FR)	ASO(BR) NSO(FR)	NS	NS	NS
15-043	U/N [2]	IO	IO	NS	NS	NS	NS	NS

15-070	U/N	NO	ASO(BR) ISO(FR)	ASO(BR) NSO(FR)	ASO(BR) NSO(FR)	ASO(BR) FSO(FR)	IO	PSO(BR) NS(FR)
15-084	Irene Reef	ASO(BR) NSO(FR)	ASO(BR) ISO(FR)	ASO(BR) NSO(FR)	ASO(BR) NSO(FR)	ISO(BR) FSO(FR)	PSO(BR) ISO(FR)	PSO(BR) NSO(FR)
15-089	Endeavour Reef (E) [5]	ASO(BR) NSO(FR)	ASO(BR) ISO(FR)	ASO(BR) ISO(FR)	ASO(BR) ISO(FR)	NS	NS	NS
15-095	Evening Reef	ASO(BR) NSO(FR)	ASO(BR) ISO(FR)	ASO(BR) NSO(FR)	ISO(BR) NSO(FR)	PSO(BR) NSO(FR)	PSO(BR) ISO(FR)	PSO(BR) NS(FR)
16-015	Mackay Reef [1]	ASO(BR) NSO(FR)	NS	NS	NS	NS	NS	NS
16-023	Rudder Reef (E)	NO	IO	AO	ASO(BR) PSO(FR)	ASO(BR) FSO(FR)	PSO(BR) ISO(FR)	PO
16-024	U/N	NO	IO	AO	AO	PSO(BR) FSO(FR)	PO	PSO(BR) NS(FR)
16-026	Tongue Reef (W) [3]	NO	NS	NS	NS	NS	NS	NS
16-026	Tongue Reef (E) [3]	NS	ASO(BR) NSO(FR)	NSO(BR) NS(FR)*	NS	NS	NS	NS
16-057	Hastings Reef [4]	NO	NO	NS	NS	NSO(BR) FSO(FR)	NS	NS
16-060	Michaelmas Reef [6]	NS	NS	NS	NS	ISO(BR) FSO(FR)	NS	NS

16-064	Arlington Reef (W) [3]	NSO(BR) ASO(FR)	NS	NS	NS	NS	NS	NS
16-064	Arlington Reef (E) [3]	NS	ASO(BR) ISO(FR)	ASO(BR) NS(FR)*	NS	NS	NS	NS
16-049	Green Island Reef [1]	NO	IO	NS	NS	NS	NS	NS
16-068	Thetford Reef	NO	NO	ASO(BR) NS(FR)*	PSO(BR) NSO(FR)	PSO(BR) FSO(FR)	ISO(BR) ASO(FR)	PSO(BR) ASO(FR)
16-071	Moore Reef [6]	NS	NS	NS	NS	ASO(BR) FSO(FR)	NS	NS
16-073	Elford Reef (E)	NO	NO	NSO(BR) NS(FR)*	NSO(BR) NS(FR)*	NS	NS	NS
17-001	Sudbury Reef [3]	NO	NS	NS	NS	NS	NS	NS
17-004	Scott Reef	NS	ISO(BR) NSO(FR)	ASO(BR) NSO(FR)	ASO(BR) ISO(FR)	ASO(BR) FSO(FR)	PSO(BR) ISO(FR)	NS
17-006	Maori Reef [3]	NO	NS	NS	NS	NS	NS	NS
17-011	Coates Reef	NS	AO	AO	AO	PSO(BR) NS(FR)*	PO	NS
17-014	Hedley Reef [7]	NS	NS	NS	ASO(BR) NS(FR)*	NS	NS	NS
17-016	McCulloch Reef [3]	NO	NS	NS	NS	NS	NS	NS

17-023	Cayley Reef	NS	NS	AO	ASO(BR) ISO(FR)	ASO(BR) NS(FR)*	PSO(BR) ISO(FR)	NS
17-034	Feather Reef	NS	NO	NO	ISO(BR) NSO(FR)	ASO(BR) ISO(FR)	AO	NS
17-047	Eddy Reef [4]	NS	NS	NSO(BR) NS(FR)*	NS	AO	AO	NS
17-051	Beaver Reef [7]	NS	NS	NS	NS	NS	ASO(BR) NS(FR)*	NS
17-064	Taylor Reef [4]	NS	NS	NSO(BR) NS(FR)*	NS	ASO(BR) ISO(FR)	ASO(BR) NS(FR)*	NS
18-026	U/N [3]	NS	NS	NSO(BR) NS(FR)*	NS	NS	NS	NS
18-030	Kelso Reef [5]	NS	NS	NS	ISO(BR) NSO(FR)	NS	ASO(BR) NS(FR)*	NS
18-031	Little Kelso Reef	NS	NS	NS	ASO(BR) NSO(FR)	ASO(BR) NSO(FR)	ISO(BR) ASO(FR)	NS
18-075	John Brewer Reef	NS	NS	NS	NO	NO	IO	NS
18-078	Lodestone Reef	NS	NS	NS	ASO(BR) NSO(FR)	PSO(BR) ISO(FR)	NS	NS

Key to codes (numbers shown in superscript; see Table 7) used to indicate operational changes to the annual sampling program.

1 Reefs that were dropped from the annual sampling program due to the local introduction of *A. planci* control programs that potentially modified the natural dynamics and characteristics of the local starfish population;
2 Reefs that were dropped from the annual sampling program to accommodate the staged southward expansion of the survey area;
3 Reefs that were dropped from the annual sampling program due to logistic and/or operational difficulties such as highly patchy distribution of suitable continuous reef habitats or exceedingly large size of reef structure with a corresponding need for extended travel away from the mother ship;
4 Entire reef or individual reef zone not surveyed during certain years due to cyclonic activity in the survey area;
5 Reefs dropped from the annual sampling program due to financial constraints arising from operational changes to the survey program;
6 Additional reefs located directly offshore Cairns - opportunistic once-off surveys in 1998-99 due to the availability of limited carry over funds;
7 Substitute reef surveyed due to inaccessibility of other regular sampling reef due to severe weather conditions.
* Reef zone not surveyed (NS) due to severe weather conditions.

Note: All reefs added to the annual sampling program in order to (i) either replace previously sampled reefs or (ii) to geographically expand the survey area were selected haphazardly.