CRC REEF RESEARCH CENTRE TECHNICAL REPORT No. 32

Crown-of-thorns starfish (*Acanthaster planci*) in the central Great Barrier Reef region. Results of fine-scale surveys conducted in 1999-2000.

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A report funded by the CRC Reef Research Centre.

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National Library of Australia Cataloguing-in-Publication entry

Crown-of-thorns starfish (*Acanthaster planci*) in the central Great Barrier Reef region. Results of fine-scale surveys conducted in 1999-2000.

Bibliography.
Includes index.
ISBN 1 876054 52 2

1. Crown-of-thorns starfish - Queensland - Great Barrier Reef. 2. Ecological surveys - Queensland - Great Barrier Reef. I. Engelhardt, Udo, 1962- . II. Cooperative Research Centre for the Great Barrier Reef World Heritage Area. (Series: Technical report (Cooperative Research Centre for the Great Barrier Reef World Heritage Area); 32).

593.9309943

This publication should be cited as:
Engelhardt, U., Hartcher, M., Taylor, N., Cruise, J., Engelhardt, D., Russell, M., Stevens, I., Thomas, G., Williamson, D., & Wiseman, D. (2001)
Crown-of-thorns starfish (Acanthaster planci) in the central Great Barrier Reef region. Results of fine-scale surveys conducted in 1999-2000.
CRC Reef Research Centre
Technical Report No. 32
Townsville; CRC Reef Research Centre, 100 pp.

Published by the Cooperative Research Centre for the Great Barrier Reef World Heritage Area ? 2001

Further copies may be obtained from CRC Reef Research Centre, c/- James Cook University, Townsville, QLD 4811.

Printed by James Cook University.

FOREWORD

The interpretation of the results of this study is controversial. This report suggests that crown-of-thorns starfish outbreaks are becoming more frequent. However, the question of how many years pass between crown-of-thorns outbreaks is one for which we do not have a definite answer. It is currently the subject of scientific debate.

There have only been three documented waves of outbreaks of crown-of-thorns starfish, with two periods between waves. With no historical information about outbreaks of crown-of-thorns starfish on the Great Barrier Reef prior to the 1960s, it is difficult to know whether the time between waves of outbreaks is changing.

The fine-scale surveys have monitored numbers of crown-of-thorns starfish on individual reefs in greater detail than previously. These surveys have documented high densities on the same reefs within five years. Because previous studies have not followed populations in such detail, it is not clear whether this represents a change in the population dynamics of crown-of-thorns starfish or has previously gone undetected during a wave of outbreaks.

Only the long-term monitoring program (run by the Australian Institute of Marine Science and supported by CRC Reef) has used the same method to count crown-of-thorns starfish in more than one wave of outbreaks. An increase in the frequency of crown-of-thorns outbreaks is not indicated by this program (Miller I. 2000. *Historical patterns and current trends in the broadscale distribution of crown-of-thorns starfish in the Northern and Central sections of the Great Barrier Reef.* Ninth International Coral Reef Symposium, Bali, October 2000).

The CRC Reef is undertaking a detailed comparison of the results of the fine-scale surveys and the long-term monitoring program at the time of this report going to print.

Dr Russell Reichelt, CEO, CRC Reef Research Centre

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PREFACE

For nearly forty years, the crown-of-thorns starfish (COTS) has been a subject of keen observation and passionate debate. Since an outbreak was first seen at Green Island in 1962, the Great Barrier Reef (GBR) has had two outbreaks come and go, and a third is under way.

Are the outbreaks a new phenomenon or has the GBR been experiencing outbreaks for millennia? Are the outbreaks natural phenomena or are they caused by human activities? Can the GBR survive COTS outbreaks? Hypotheses have been proposed to answer these critical questions and others, but the balance of evidence has not yet tipped decisively in favour of alternative hypotheses.

In the last three years, a new set of questions about COTS outbreaks is being asked. Is the interval between outbreaks decreasing? Are COTS population dynamics changing from acute outbreaks to chronic infestations? If COTS population dynamics change, will hard coral communities survive, or will there be a long-term decline in hard corals on the GBR? As with other questions related to COTS, opinions as to the answers vary.

The results in this study are the most detailed available on the population dynamics of COTS. They give us a better understanding of how an outbreak can develop and may enable us to propose better answers to some of the long-standing questions about COTS.We have only six years of this detailed data. Consequently, to put the results from the fine-scale monitoring in a historical perspective, we have to compare them with other results, mostly collected by manta tow. The fine-scale surveys use a very different methodology to the manta tows and these differences must be acknowledged when comparisons are made. In addition, the GBR is currently experiencing only its third documented COTS outbreak. So, it is difficult to make any statement about trends in outbreaks such as their severity, duration or periodicity.

Currently, the CRC Reef Research Centre is undertaking a detailed analysis of the manta tow and fine-scale survey COTS data sets. This analysis will provide the most robust synthesis yet of our knowledge of the dynamics of COTS outbreaks. I look forward to the results of this analysis and the opportunity to move closer to resolving some of the questions regarding the COTS phenomenon.

David Wachenfeld, Acting Manager (Research and Monitoring Co-ordination)

Great Barrier Reef Marine Park Authority

EXECUTIVE SUMMARY

Intensive transect-based surveys of crown-of-thorns starfish (*Acanthaster planci*) and associated live hard coral cover were conducted on 19 mid-shelf reefs located in the Cairns and Central Sections of the Great Barrier Reef Marine Park.

?? The 1999-00 surveys recorded a total of 3,996 *A. planci* on 19 reefs. In 700 benthic transects, there were 939 (23.5% of total) juvenile starfish, 1,659 (41.5%) sub-adults and 1,398 (35.0%) adult starfish. The dominance of sub-adults indicates that populations of crown-of-thorns starfish (COTS) are growing on many survey reefs. This is likely to lead to renewed active outbreaks of adult starfish throughout much of the survey area.

?? *Juvenile starfish (esimated age 1):* The average density of juvenile *A. planci* across all reefs surveyed in 1999-00 was 1.34 individuals per 250 m^2. This is the second highest density of juvenile starfish recorded in the six years since the inception of the fine-scale surveys in 1994-95. The highest average density of 3.30 starfish per transect across all reefs was recorded in 1998-99. The 1998-99 estimate provided an early indication of the renewed outbreaks currently developing on reefs in both the Cairns and Central Sections of the Great Barrier Reef Marine Park.

Juvenile *A. planci* were recorded throughout the study area. Rudder Reef (offshore Port Douglas) and John Brewer Reef (offshore Townsville) recorded the highest numbers with 125 and 100 starfish, respectively. Potentially unsustainable juvenile densities were found on reefs which were both affected and unaffected by recent *A. planci* outbreaks. In areas that had recently suffered significant starfish-induced coral mortality (i.e. remnant live hard coral cover of <10%), we noted a preference of juvenile and sub-adult starfish to feed on small recently recruited, hard corals. These starfish cohorts could significantly impact the onset and progress of coral recovery on starfish-affected reefs.

?? *Sub-adult starfish (estimated age 2):* As predicted after completing the 1998-99 fine-scale surveys, densities of sub-adult starfish on many survey reefs have risen significantly. Currently, the combined densities of sub-adult and adult starfish are exceeding threshold levels on 11 (57.9%) of 19 reefs surveyed. This has led to the re-classification of these reefs as incipient reef-wide (IO) or incipient spot outbreaks (ISO). It is of particular concern that incipient outbreaks were recorded on 10 mid-

shelf reefs that have experienced active COTS outbreaks in recent years. Renewed outbreaks appear to be developing on these reefs, three to five years after previous outbreaks. This casts significant doubt over the long-term sustainability of the outbreak phenomenon in parts of the central Great Barrier Reef (GBR) region. A lack of live hard coral cover on many of these reefs may prevent the full maturation of the large 1997-98 cohort of starfish in some areas. However, their current feeding activity is already impacting coral recovery on reefs which have been previously affected. Our observations during the 1999-00 surveys suggest that sub-adult and juvenile starfish fed preferentially on small, recently settled, hard coral recruits. This pattern is likely to impact significantly on the recovery process, at least in the short term.

?? *Adult starfish (estimated age 3 or older)* exceeded sustainable densities on seven (36.8%) of the 19 reefs surveyed in 1999-00, with two reefs (17-034, 17-047) recording actively outbreaking populations in both front- and back-reef zones. On five reefs (16-068, 17-051, 17-064, 18-030, 18-031), outbreaking populations of adult starfish were restricted to either the back- or the front-reef zone.

?? The cumulative total of mid-shelf reefs and zones within these reefs that have been (post-outbreak), are currently (active outbreak) or soon will be (incipient outbreak) affected by COTS outbreaks has reached 100%. Since the inception of the fine-scale surveys in 1994-95, none of the core reefs or zones within these reefs that have been surveyed regularly have escaped the latest COTS outbreak episode. Fine-scale survey reefs (x reefs) were initially chosen at random and are deemed to be representative of mid-shelf reefs within the survey area (y reefs). Therefore, our findings now suggest that, since early-mid 1990, live hard coral cover on virtually all mid-shelf reefs between Lizard Island and Townsville is being affected by the current outbreak phenomenon. Observations and reports from reef-users also suggest that a significant number of outer- and inner-shelf reefs adjacent to our survey area are being affected by increasing numbers of *A. planci.*

Our most recent surveys have confirmed the widespread nature and effects of the large 1997-98 cohort of *A. planci* on mid-shelf reefs in the central GBR region. This cohort, identified by fine-scale surveys in 1998-99, is the largest and geographically most widespread age class of *A. planci* recorded on the GBR. As this cohort approaches maturity (age of first reproduction

is estimated to be reached by November / December 2000), there is potential for further significant impacts on coral communities throughout the central GBR region.

The 1999-00 survey results suggest that some mid-shelf reefs in this region will soon experience renewed outbreak activity only three to five years after the previous outbreak episode. This pattern suggests a possible shift from the previously recorded 15 to 17 year gap of starfish outbreaks in this region. A significant shortening of periodicity is likely to be unsustainable in the long-term because hard coral communities on affected reefs would not have sufficient time to completely recover and regenerate. Increasingly chronic outbreaks of *A. planci* could result in many permanently degraded reefs that are unable to recover from high-frequency ecological disturbances. Apart from the obvious and serious ecological implications, our findings also suggest there would be significant economic impacts of such a scenario. The identified trends apply to reefs located offshore Port Douglas and Cairns; the scenario outlined above would have serious implications for the future operations and sustainability of the regional reef tourism industry.

Consequently, efforts to assess any detrimental trends and conditions should be given the highest priority. A long-term strategic response to further studies of this possibly increasing outbreak frequency and/or intensity is urgently needed. An increasingly chronic outbreak situation could indicate an 'unnatural' (i.e. human-induced) process. Therefore, there should be a renewed focus on evaluating the role of activities such as fishing of the natural predators of *A. planci* and increased nutrients in coastal waters as a result of regional land use patterns. We suggest that scientific risk-assessment analyses should be carried out as a matter of the highest priority. This scientific approach is the only feasible way to determine the probabilities that the factors mentioned above are contributing to the apparently changing characteristics of this important phenomenon.

Intensive fine-scale monitoring of *A. planci* and associated live hard coral cover should be continued and extended to maximise the chance of identifying further reef degradation and reduced coral recovery rates in the study area in a timely manner.

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 outbreaks in the 1960s and 1980s, populations of *A. planci* were first observed on Green Island Reef off Cairns ($16^{o}46'S$) and surrounding reefs (Moran 1986). However, surveys of starfish populations were not initiated until several years later, when the outbreaks had progressed several hundreds of kilometres from their geographic origin (Dight *et al.* 1990, Moran *et al.* 1992).

Despite considerable research, particularly from the mid-1980s to the mid-1990s, the cause(s) of *A. planci* outbreaks on the GBR and elsewhere remain unknown (see Engelhardt and Lassig 1997). A lack of reliable data on the dynamics and age structure of *A. planci* populations before, during and after outbreaks is a major reason for the failure of the recent research effort to better understand the cause(s) of outbreaks.

Surveys of *A. planci* populations on the GBR and in the Indo-Pacific region have used several techniques, including timed swim searches (Pearson and Endean 1969, Kenchington 1976), spot checks (Pearson 1972) and manta tows (Moran *et al.* 1985, Oliver *et al.* 1995, Sweatman *et al.* 1998). However, few of these surveys provided accurate estimates of population densities and age structures (Birkeland and Lucas 1990). Population field and modelling studies have suffered from the lack of suitable data. Such information is, however, critical for improving our understanding of the factors and mechanisms that initiate outbreaks.

Accurately assessing populations with low densities or substantial numbers of small juvenile starfish has posed particular difficulties. Juvenile *A. planci* (estimated age 1) are not easily sampled and are rarely seen in the field because of their cryptic behaviour and nocturnal feeding habits (Doherty and Davidson 1988, Johnson *et al.* 1991). Braod-scale survey techniques, such as manta towing, are 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 are better suited to accurately census low-density populations

of starfish. Benthic belt transects have recently been used on the GBR to provide more reliable estimates of population densities and age structures (Engelhardt *et al.* 1997, Mapstone *et al.* 1998, Mapstone and Ayling 1998). Using an intensive, transect-based method, the most recent, third-recorded outbreak was detected much earlier than had previously been possible (Engelhardt and Lassig 1997).

This report outlines the results of intensive fine-scale surveys of *A. planci* and associated live hard coral cover conducted on mid-shelf reefs in the Cairns and central sections of the GBRMP in 1999-00.

1.2 Objectives

The surveys' objectives were to:

- ?? obtain reliable estimates of *A. planci* population densities and associated live hard coral cover on mid-shelf reefs in the survey area;
- ?? accurately determine size-frequency distributions within *A. planci* populations to facilitate the identification of probable age classes or 'pseudo-cohorts';
- ?? if present, detect early signs of possible new and emerging outbreaks to provide an early warning of likely future trends; and
- ?? identify differences in the abundance and/or age composition of starfish populations at three different spatial scales - regional (latitudinal), between reef (local) and within-reef (zonal).

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

2. MATERIALS AND METHODS

2.1 Regional or latitudinal bands

We surveyed 19 mid-shelf reefs across three regional or latitudinal bands which each band covered 1.5 degrees of latitude. The latitudinal bands covered the following geographic regions:

Latitudinal band 1	($14^{o}31'$-$16^{o}00'$S)
Latitudinal band 2	($16^{o}01'$-$17^{o}30'$S)
Latitudinal band 3	($17^{o}31'$-$19^{o}00'$S)

2.2 Individual survey reefs

Since their inception in 1994-95, fine-scale surveys of *A. planci* have focused on mid-shelf reefs because hydrodynamic modelling has postulated strong but variable connectivity of these reefs of the central GBR region (latitudes $14^{o}30'$-$19^{o}30'$S) (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), and are seldom exposed to competent *A. planci* larvae from upstream sources. Most field data on *A. planci* distribution across the GBR also indicate that mid-shelf reefs support larger numbers of starfish than inner- or outer-shelf reefs (Moran *et al.* 1992, Engelhardt, unpublished data).

All mid-shelf reefs surveyed since 1994-95 were selected haphazardly. However, the original set of survey reefs has been modified over the past six years due to logistic and operational considerations. Individual reefs have been dropped or added to the program for different reasons:

?? Some reefs were dropped due to the initiation of localised *A. planci* control programs that may have modified the natural dynamics and characteristics of the local starfish population;

?? Some reefs were dropped to accommodate the 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 some years due to severe weather conditions in the survey area.

In all instances until mid-1997, the sampling program was modified after consultation with members of the Crown-of-Thorns Starfish Research Committee (COTSREC) which was an independent advisory body providing expert advice about the starfish to the Great Barrier Reef Marine Park Authority (GBRMPA). A list of reefs surveyed since 1994-95 is provided in Appendix A.

In August 1998, the abolition of two staff positions in the COTS program at the GBRMPA reduced the financial support available for the survey program. Furthermore, full responsibility for the operation of the survey program was formally transferred from GBRMPA to CRC Reef Research Centre prior to the 1998-99 survey season. In response to these operational changes and the resulting financial implications, additional reefs had to be dropped from the annual sampling program. All reefs surveyed in 1999-00 were located along a mid-shelf trajectory from the Cairns section in the north to the central section of the GBRMP in the south (Figure 1). Reefs were surveyed between October 1999 and April 2000.

2.3 Within-reef zones

At each survey reef, we sampled an equal number of sites and replicate transects within each of two within-reef zones: the protected back-reef zone (BR) and the exposed front-reef zone (FR). The exposed FR was defined as reef areas facing more or less directly south-east into the prevailing winds that affect the GBR region for most of the year. The BR comprised those parts of a reef that were largely protected from the south-easterly 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 independently surveyed a total of 10 sites within each of the two within-reef zones. Mapstone and Ayling (1998) showed that to visually assess the abundance of benthic organisms such as *A. planci*, belt transects of 50 x 5 m provide the least biased estimates of density within the logistic and operational constraints of many survey programs. We sampled two replicate 50 x 5 m (250 m^2) transects at each site. Both site selection and transect placement were haphazard.

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

A visual estimate of total live hard coral cover (LHCC) within each transect was recorded. LHCC were recorded as 10%-range estimates; i.e. 5-15%, cover 25-35% cover, 40-50% cover etc. A single 5%-range estimate was used where LHCC was estimated to be less than 5%. To calculate the mean percent LHCC across individual reef zones and reefs, we used the midpoints of the range estimates (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%. In all cases, the standard error (SE) for calculated visual LHCC estimates was less than the 5% margin which was set 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). An overview of the survey and sampling design used in 1999-00 is provided in Table 1.

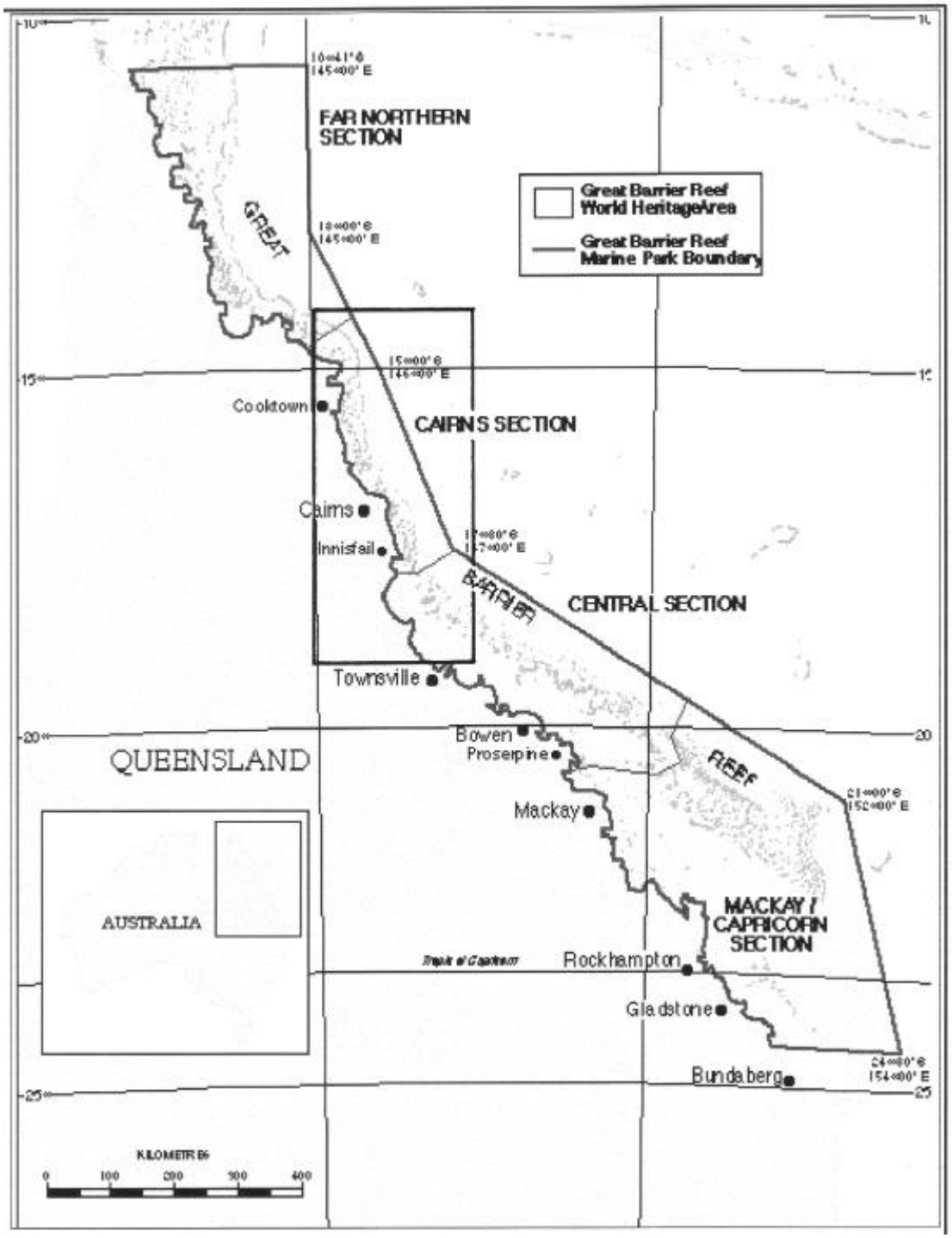


Figure 1. Map of the Great Barrier Reef Marine Park showing the 1999-00 survey area (central boxed area) covering the Cairns and central sections of the Marine Park.

Table 1. The sampling design used for *A. planci* fine-scale surveys in 1999-00.

Latitudinal band	Reef ID number [1]	Reef name	Zones per reef	Sites/transects per zone
1 ($14^{o}31'$-$16^{o}00'$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 / FR	10 x 2
	15-084	Irene Reef	BR / FR	10 x 2
	15-095	Evening Reef	BR / FR #	10 x 2
2 ($16^{o}01'$-$17^{o}30'$S)	16-023	Rudder Reef	BR / FR	10 x 2
	16-024	Unnamed Reef	BR / FR #	10 x 2
	16-068	Thetford Reef	BR / FR	10 x 2
	17-004	Scott Reef	BR / FR #	10 x 2
	17-011	Coates Reef	BR / FR	10 x 2
	17-023	Cayley Reef	BR / FR	10 x 2
3 ($17^{o}31'$-$19^{o}00'$S)	17-034	Feather Reef	BR / FR	10 x 2
	17-047	Eddy Reef	BR / FR	10 x 2
	17-051	Beaver Reef *	BR only #	10 x 1
	17-064	Taylor Reef *	BR only	10 x 1
	18-030	Kelso Reef *	BR only	10 x 1
	18-031	Little Kelso Reef	BR / FR	10 x 2
	18-075	John Brewer Reef	BR / FR	10 x 2
TOTAL	**19 reefs**		**35 zones**	**350 sites 700 transects**

[1] Reef ID numbers as per GBRMPA Reef Gazetteer

* due to severe weather conditions, only the back-reef zone was sampled.

excluded from the analyses of latitudinal differences in COTS age class abundances (see Results 3.3.1) to achieve a balanced sampling design as required for Kruskal-Wallis analyses. Reef zones excluded from the full analyses were selected at random.

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

In the absence of reliable ageing techniques for *A. planci*, 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 GBR (Figure 2). This curve was constructed using size-frequency information from more than 3,500 starfish measured during previous surveys (Engelhardt, unpublished data). Peaks (modes) in the size-frequency distribution of *A. planci* were deemed to indicate probable age classes or 'pseudo-cohorts'. The 'pseudo-cohorts' were used to assign *A. planci* observed in 1999-00 to one of three probable age classes: juvenile starfish (estimated age 1, $\leq$13 cm), sub-adult starfish (estimated age 2, 14-25 cm) and adult starfish (estimated age 3 or older, $\geq$26 cm). The broad size/age categories correspond with published information on probable size and age relationships in *A. planci*, including natural, *in situ* (Zann *et al.* 1987, 1990, Zann and Vuki 1992) and laboratory-based estimates of 'size-at-age' (Yamaguchi 1974, Lucas 1984). Published estimates of juvenile and sub-adult growth are variable but provide a useful tool for assessing recent recruitment history. For example 12-month-old starfish may range from 4.5-11.5 cm across, with 24-month-old starfish commonly between 15-24 cm.

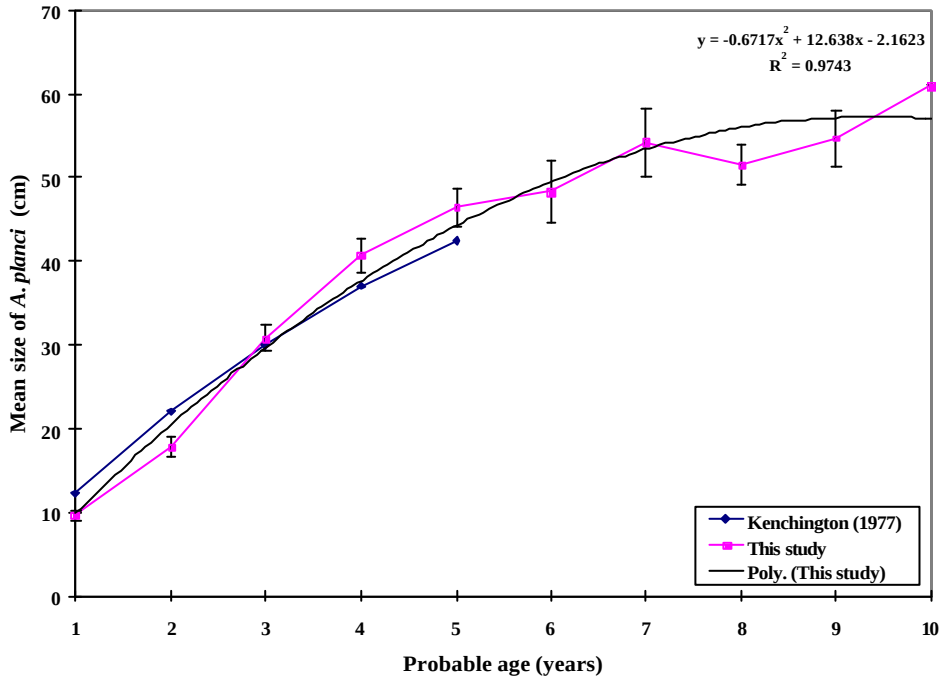


Figure 2. Estimated size-at-age plot for *A. planci* in the central GBR region. Error bars show standard errors ($\pm$1 SE). Poly refers to the second-order polynomial function used to fit the curve for this data set.

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, SE) of adult starfish was $\geq$0.75 individuals per 250 m^2 transect. This threshold 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 0.25 - 0.375 per 250 m^2). The threshold of 0.75 starfish per 250 m^2 used in this study is more conservative and takes some additional variables, such as higher coral cover and seasonally reduced feeding rates, into account.

Individual reefs were classified using a hierarchical principle as summarised in Table 2. Selected data subsets were analysed in the order shown in Table 2, ie. the ADULT subset first, the SUB-ADULT AND ADULT subset second, the JUVENILE subset next and so on, with the highest order classification used to define reef or zonal status.

The threshold of 2.5 (mean-1 SE) juvenile *A. planci* per 250 m^2 used to define possible Future Spot and/or reef-wide outbreaks (FSO/FO respectively) is based on observations over the past six survey seasons. In some instances, average juvenile densities of approximately 1.25 individuals per transect provided a reliable indication of new and emerging outbreaks (Engelhardt, unpublished data). However, we used a more conservative figure of 2.5 juveniles per transect before classifying any of the reefs surveyed in 1990-00 as Future Outbreak. Throughout the report, we refer to juvenile densities of between 1.25 and 2.5 (mean-1 SE) juvenile *A. planci* per 250 m^2 as *significant* densities. Estimates above the critical threshold of 2.5 (mean -1 SE) juvenile *A. planci* are considered *unsustainably high* densities.

Table 2 Reef status classification scheme - overview of data subsets and criteria used to determine the status of individual reefs and within-reef zones surveyed in 1999-00.

Data subset	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 SE) **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 SE) **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 SE) **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 SE) **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 SE) **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 subsets **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 subsets **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

2.7 Statistical analyses

Data for individual reefs and within-reef zones were first analysed using simple descriptive statistics (Figures 3.1 to 3.19).

Non-parametric Kruskal-Wallis tests (Kruskal and Wallis 1952) were used to investigate significant differences between the abundance of 'pseudo-cohorts' of *A. planci* in the three spatial scales. Non-parametric tests were used because starfish counts were non-normally distributed. As a result of many 'zero' counts, commonly advocated data transformations did not achieve acceptable levels of 'normality' to use standard parametric ANOVA techniques. We used Kruskal-Wallis analyses of variance by rank procedures to test for significant differences between sample medians.

Kruskal-Wallis analysis tests the null hypothesis that the medians of the selected variable within each of the selected levels are the same. Data from all levels are combined and ranked from smallest to largest. The average rank is computed for the data at each level. Where the P-value is less than 0.05, there is a statistically significant difference between the medians at the 95.0% confidence level. Box-and-Whisker plots throughout this report are to be interpreted as follows. The rectangular part of the plot extends from the lower quartile to the upper quartile, covering the centre half of each sample. The centre lines within each box represent the sample medians. The plus signs (+) indicate the sample means. The whiskers extend from the box to the minimum and maximum values in the sample. Notches on the plots cover a distance above and below each median. If the two notches for any pair of medians do not overlap, the difference between the medians is statistically significant at the 95% confidence level.

To achieve a balanced sampling design we omitted some subsets of the total sample data collected in 1999-00. An unbalanced design was a result of the severe weather conditions between February and April 2000 when a number of reef zones could not be surveyed. Individual reefs or zones within reefs which were excluded from particular analyses are identified in Tables 1, 4, 5 and 6.

3. RESULTS

3.1 The distribution and abundance of estimated age classes of *A. planci* in 1999-00.

Overview of results

A total of 3,996 *A. planci* were recorded on the 19 reefs surveyed. There were 939 (23.5%) juvenile starfish (est. age 1) with a further 1,659 (41.5%) sub-adults (est. age 2) and 1,398 (35.0%) adult (est. age 3) starfish recorded inside the 700 benthic transects sampled in 1999-00.

Adult *A. planci* (est. age 3 and older): Densities of adult starfish across survey reefs ranged from 0.00±0.00 (reef mean ± 1 SE) individuals per 250 m^2 recorded on four reefs (14-132b, 15-024, 16-024, 17-011) to 19.28±3.56 individuals at Feather Reef (17-034) - approximately 26 times above the sustainable density. The average density of adult *A. planci* across all reefs surveyed in 1998-99 was estimated at 1.99±0.28 starfish per 250 m^2.

Active Spot Outbreaks (ASO) were detected on five individual survey reefs (16-068, 17-051, 17-064, 18-030, 18-031). On all but one of these reefs, *A. planci* densities within the protected back-reef zone were above the limit of a sustainable population. However, Little Kelso Reef recorded an ASO in the exposed front-reef zone. At both Feather Reef (17-034) and Eddy Reef (17-047) adult densities exceeded the sustainable threshold of 0.75 starfish per 250 m^2 in both reef zones leading to their classification as Active reef-wide Outbreaks (AO). Densities of adult starfish 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 survey reefs ranged from 0.03±0.03 (reef mean ± 1 SE) starfish per 250 m^2 at Coates Reef (17-011) to 10.15±1.70 starfish at Thetford Reef (16-068). The average density of sub-adult *A. planci* across all reefs surveyed in 1999-00 was 2.37±0.20 starfish per 250 m^2. Incipient Spot Outbreaks (ISO) were detected on seven reefs (15-084, 15-095, 16-023, 16-068, 17-004, 17-023, 18-031), with a further four reefs (15-019, 15-024, 15-070,18-075) classified as supporting reef-wide Incipient Outbreaks (IO). Incipient spot and/or reef-wide outbreaks are expected to develop into active outbreaks by the summer of 2000-01. 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 survey reefs ranged from 0.90±0.38 (reef mean ± 1 SE) starfish per 250 m^2 at Kelso Reef (18-030; NB. back reef only surveyed) to 3.13±0.54 starfish at Rudder Reef (16-023). The average density of juvenile *A. planci* across all reefs surveyed in 1999-00 was 1.34±0.09 starfish per 250 m^2. This is the second highest density recorded during the past six years. Details of juvenile starfish densities for individual reefs and zones within reefs are presented in Tables 3.1 to 3.19.

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 1999-00 fine-scale surveys for individual reefs. Size-frequency information and average densities for three age classes of *A. planci* across entire reefs and within individual reef zones are provided. To help interpret the trends in adult starfish densities and live hard coral cover, we show time series data collected since the initiation of the survey program in 1994-95. Reefs or zones within reefs which were not surveyed in a particular year are indicated by NS (Not Surveyed). See glossary for other abbreviations.

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 ± 10% error). However, since 1996-97 all LHCC estimates have been recorded using higher resolution 10%-range estimates as outlined in Materials and Methods.

Aerial photographs of individual survey reefs show all sites sampled in 1999-00. Use of these aerial photographs is with permission of the GBRMPA and is covered by a formal use agreement. All reef images are oriented with the top margin pointing due north. The reef images came from photographic scans of unknown magnification and, therefore, scale bars are not included.

Figure 3. Summary of results for mid-shelf reefs surveyed in 1999-00

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

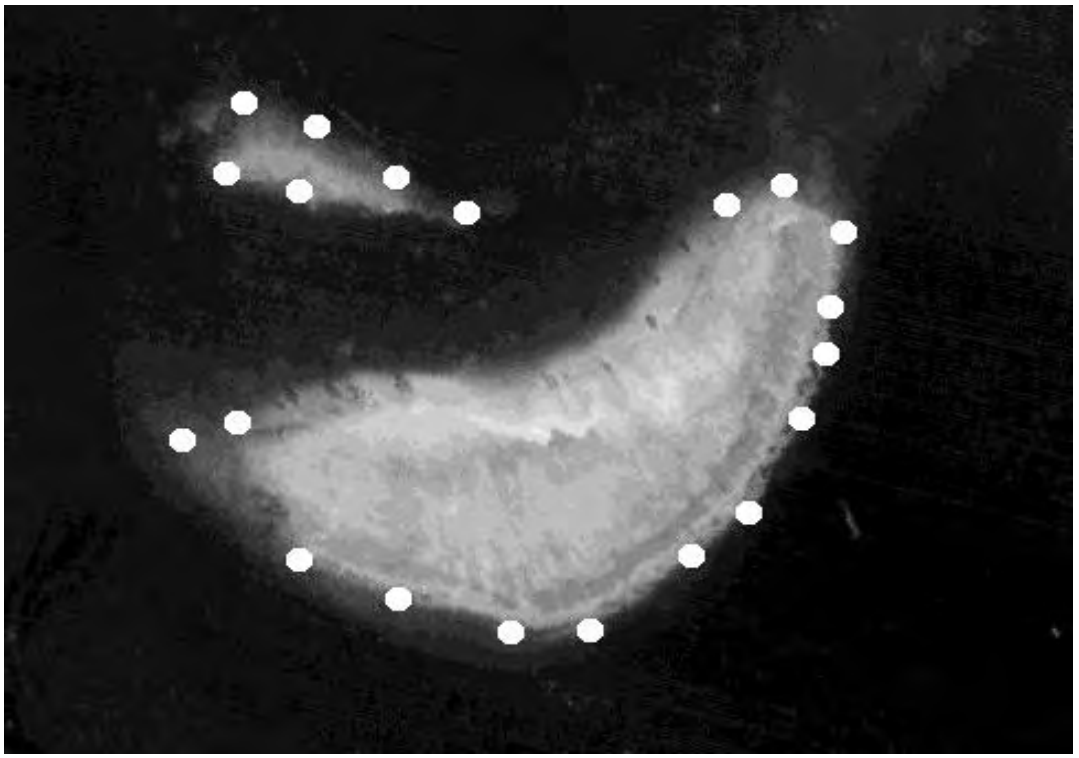


Figure 3.1.1. Aerial photograph of Rocky Islets Reef (14-132b). White dots indicate the approximate locations of the 20 sites surveyed in October 1999.

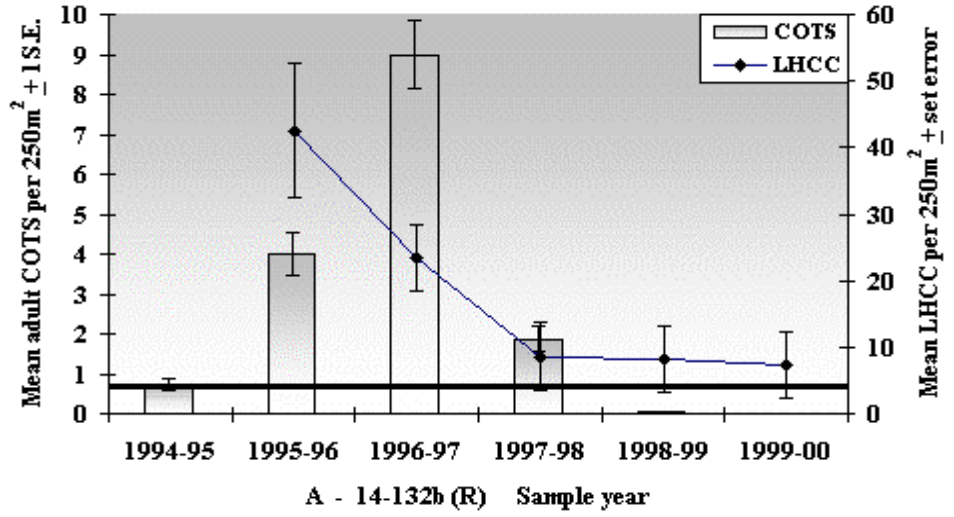
Table 3.1.a. Reef status classifications for Reef 14-132b since 1994-95.

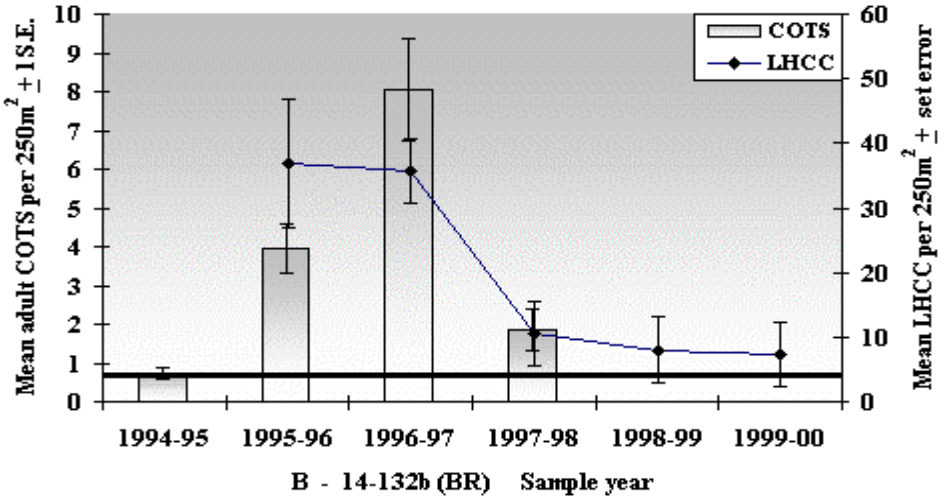
	Reef Status Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef						PSO
Front Reef						PSO
Entire Reef	IO	AO	AO	AO	PO	PO

Table 3.1.b. Mean densities (±1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1999-00. Values in brackets are total *A. planci* counts.

	Mean Densities (±1SE) (per 250 m^2)		
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**
Back Reef (BR)	1.00±0.32 (20)	0.80±0.21 (16)	0.00±0.00 (0)
Front Reef (FR)	0.65±0.18	0.75±0.19	0.00±0.00

	(13)	(15)	(0)
Entire Reef (BR+FR)	0.83±0.19 (33)	0.78±0.14 (31)	0.00±0.00 (0)





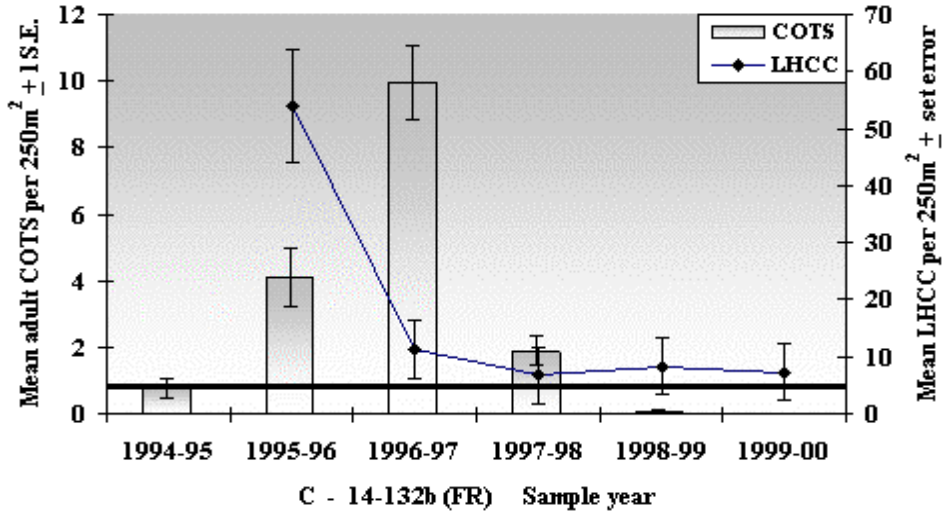


Figure 3.1.2. Reef 14-132b. The mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back-reef zone (B-BR) and in the front-reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable,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

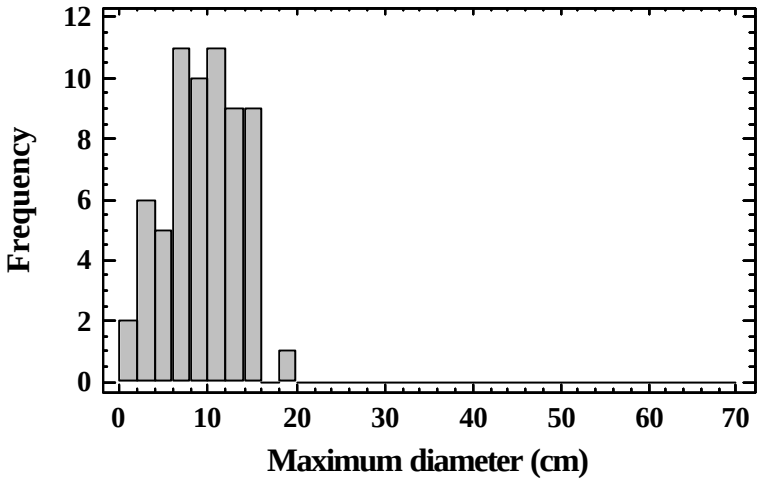


Figure 3.1.3. Size-frequency plots of *A. planci* observed at Reef 14-132b in October 1999.

Summary

Rocky Islets Reef (14-132b) remains classified as Post-Outbreaking (PO) following the collapse of the previous outbreaking population of COTS during the past two years. At the peak of the latest outbreak in 1996-97, densities of adult COTS across the entire reef were recorded at 12-times above sustainable levels. The 64 COTS recorded in 1999-00 were either juvenile (est. age 1) or sub-adult (est. age 2) starfish.

Live hard coral cover (LHCC) in both the back- and the front-reef zone remains low with 0-10% average cover. There are few signs of any significant hard coral recovery. Recently settled juvenile hard corals were subjected to significant levels of predation as a result of the feeding activities of the current juvenile and sub-adult population of COTS. It seems unlikely that these starfish cohorts will reach maturity due to current food limitations. There is a strong possibility that their feeding activities will affect the onset and magnitude of the coral recovery phase, at least in the short term.

Figure 3.2. Long Reef (15-019)

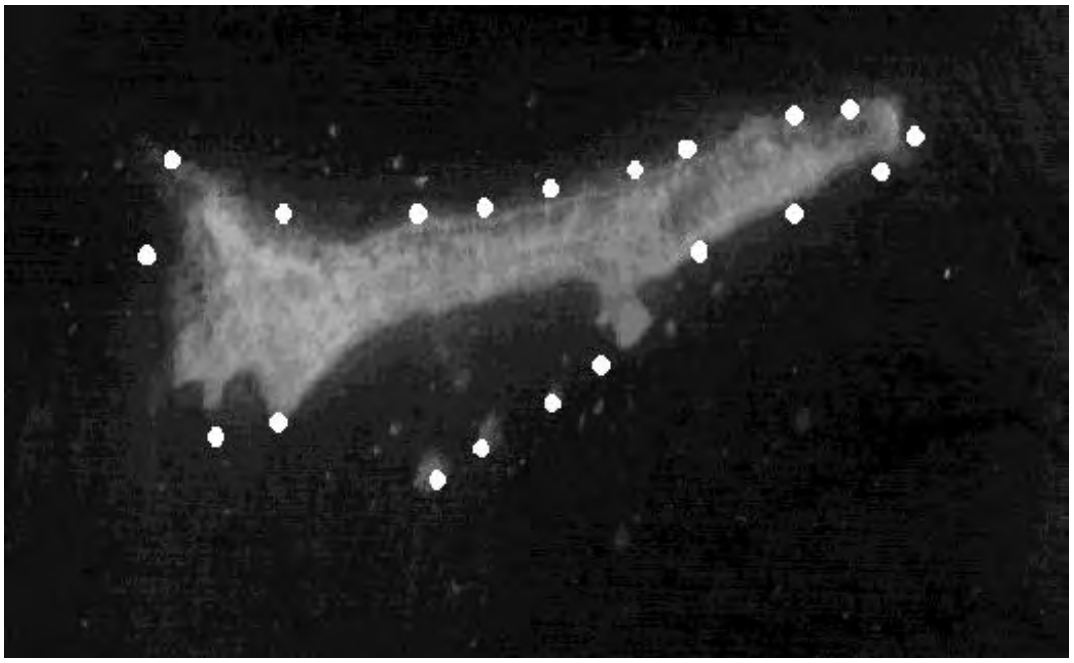


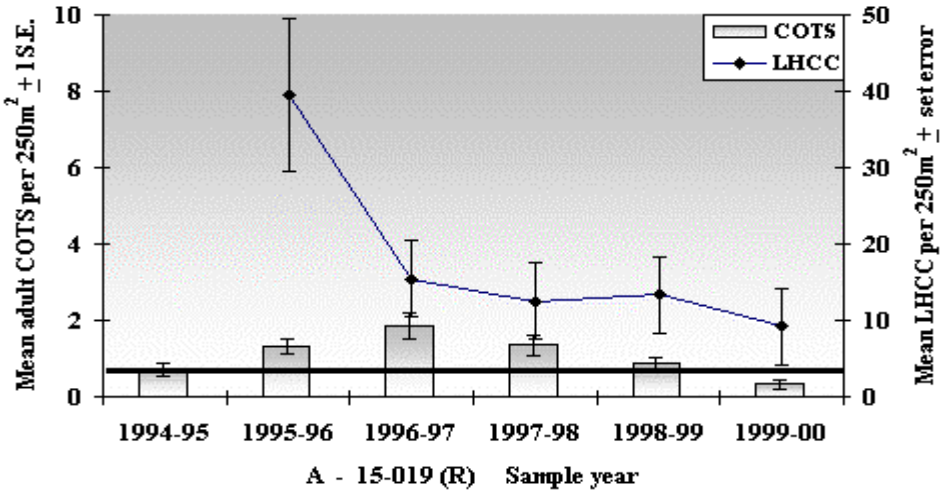
Figure 3.2.1. Aerial photograph of Long Reef (15-019). White dots indicate the approximate locations of the 20 sites surveyed in October 1999.

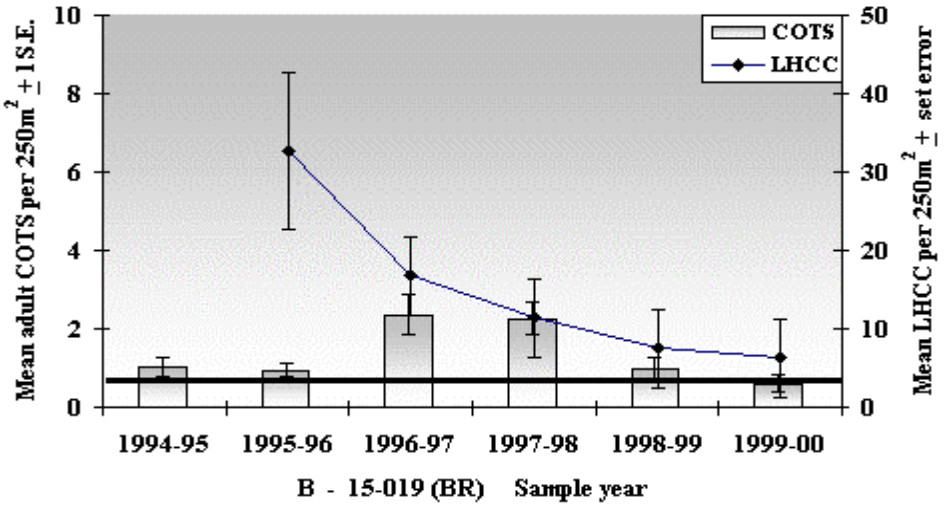
Table 3.2.a. Reef status classification for Reef 15-019 since 1994-95.

	Reef Status Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef	ASO			ASO		ISO
Front Reef	NO			PSO		ISO
Entire Reef		AO	AO		IO	IO

Table 3.2.b. Mean densities (+1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1999-00. Values in brackets are total *A. planci* counts.

	Mean Densities (±1SE) (per 250 m^2)		
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**
Back Reef (BR)	0.20±0.12 (4)	1.00±0.37 (20)	0.60±0.23 (12)
Front Reef (FR)	2.55±0.47 (51)	3.70±1.25 (74)	0.05±0.05 (1)
Entire Reef (BR+FR)	1.38±0.31 (55)	2.35±0.68 (94)	0.33±0.13 (13)





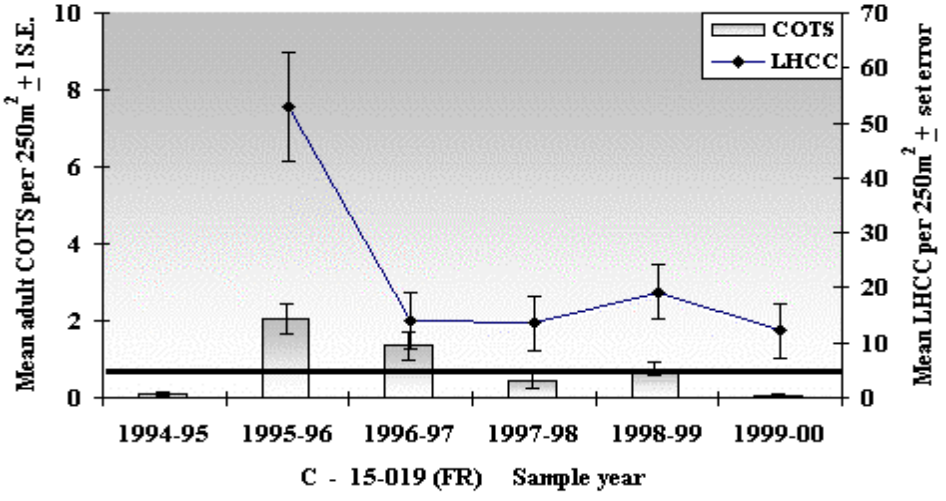


Figure 3.2.2. Reef 15-019. The mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back-reef zone (B-BR) and in the front-reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable,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

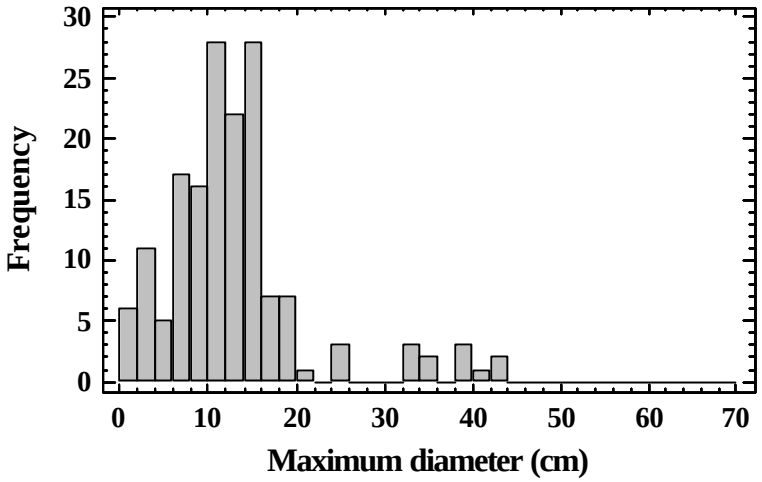


Figure 3.2.3. Size-frequency plots of *A. planci* observed at Reef 15-019 in October 1999.

Summary

The remnant population of mature COTS (est. age 3 and older) recorded at Long Reef (15-019) in 1998-99 has collapsed during the past 12 months. The density of mature starfish has declined and coincided with a further decline in live hard coral cover (LHCC) particularly in the front-reef zone where LHCC has dropped to about 10%. Average LHCC in the back-reef zone has remained unchanged at 0-10%. Both reef zones are now classified as Incipient Spot Outbreaks (ISO).

Should renewed spot outbreaks develop in the next 12 months as indicated here, then two consecutive COTS outbreaks would have affected Long Reef within three to four years. Some 149 of the 162 COTS recorded in 1999-00 were either juvenile (est. age 1) or sub-adult starfish (est. age 2). Our observations suggest that these cohorts are significantly affecting the coral recovery process. Hard coral recovery is being hampered by COTS feeding activity because recently settled juvenile corals are subject to significant levels of starfish predation.

Figure 3.3. Mackay Reefs (15-024)

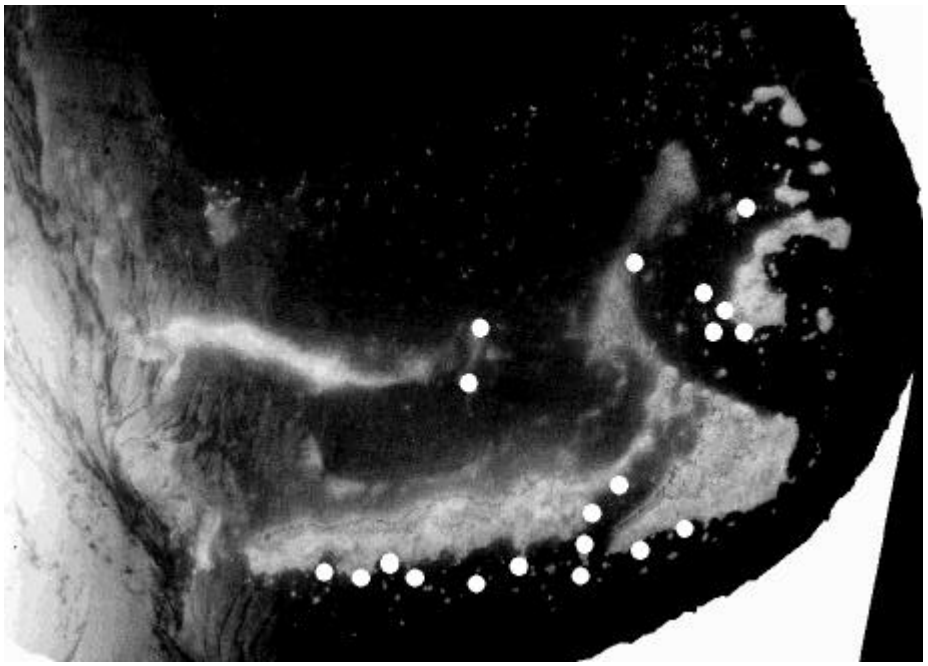


Figure 3.3.1. Aerial photograph of Mackay Reefs (15-024). White dots indicate the approximate locations of the 20 sites surveyed in October 1999.

Table 3.3.a. Reef status classification for Reef 15-024 since 1994-95

	Reef Status Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef	ASO				ASO	ISO
Front Reef	NO				PSO	ISO
Entire Reef		AO	AO	AO		IO

Table 3.3.b. Mean densities (±1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1999-00. Values in brackets are total *A. planci* counts.

	Mean Densities (±1SE) (per 250 m^2)		
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**
Back Reef (BR)	1.20±0.49 (24)	1.30±0.44 (26)	0.05±0.05 (1)
Front Reef (FR)	1.90±0.43 (13)	1.90±0.49 (38)	0.00±0.00 (0)
Entire Reef (BR+FR)	1.55±0.33 (62)	1.60±0.33 (64)	0.03±0.03 (1)

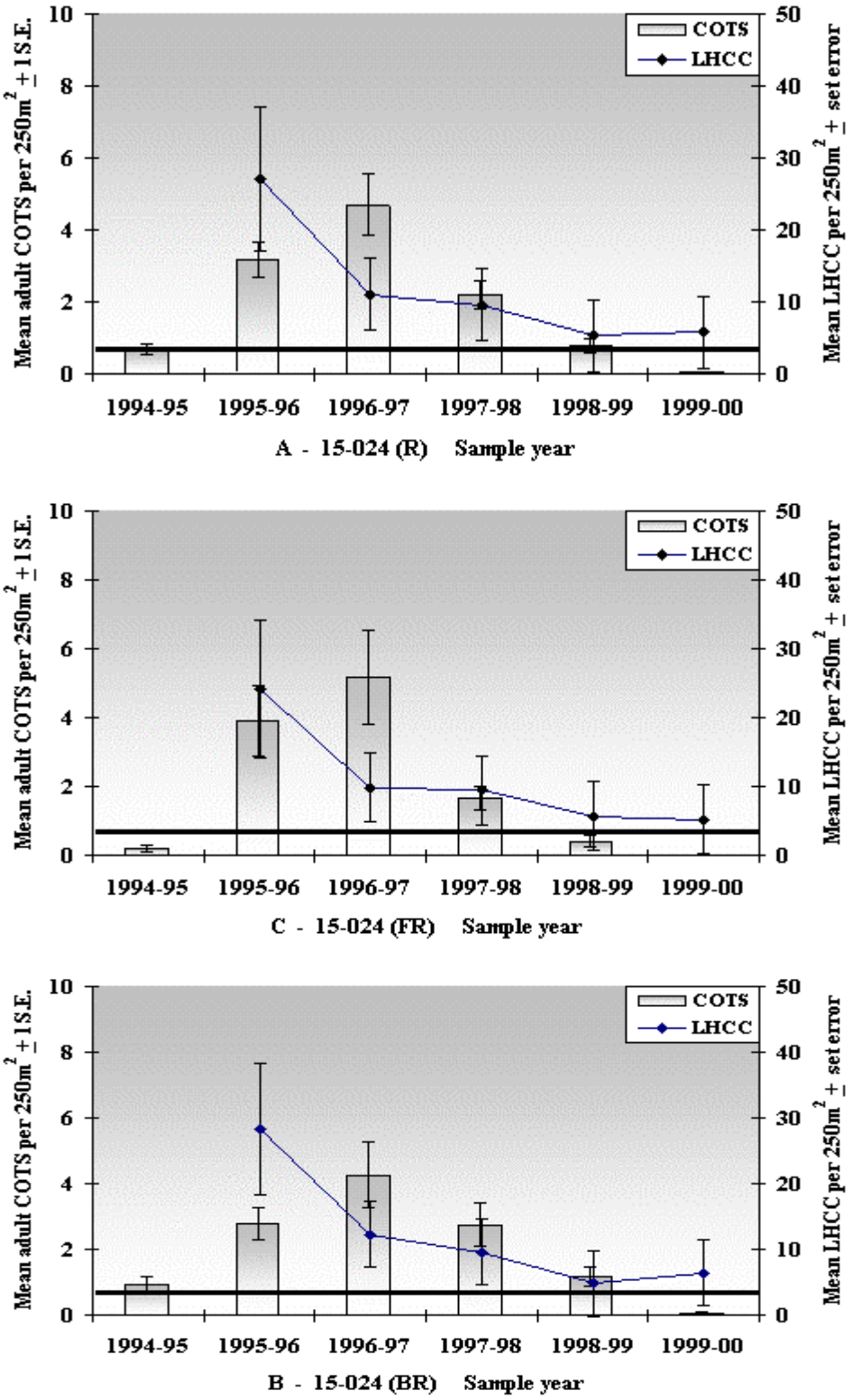


Figure 3.3.2. Reef 15-024. The mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back-reef zone (B-BR) and in the front-reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable,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

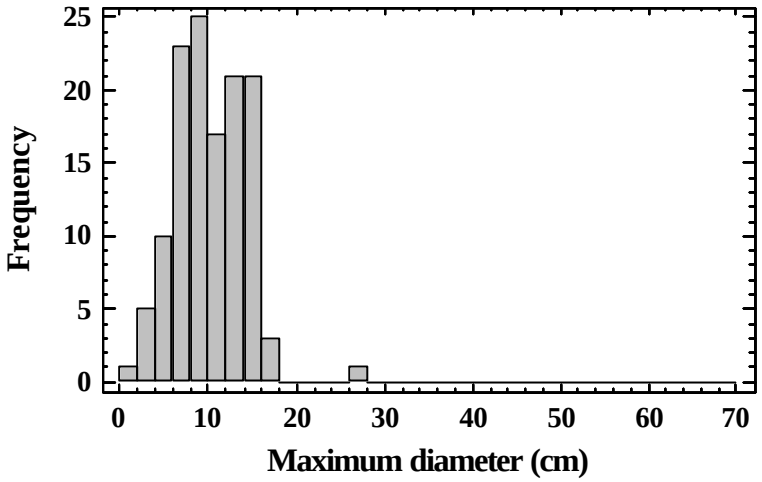


Figure 3.3.3. Size-frequency plots of *A. planci* observed at Reef 15-024 in October 1999.

Summary

Since the 1998-99 surveys, populations of mature starfish in the back- and front-reef zones at Mackay Reefs (15-024) have virtually collapsed. This follows a prolonged episode of above-sustainable COTS populations in the back- and front-reef zones that persisted for four and three years, respectively. As a result of the intense predation levels by adult starfish, live hard coral cover (LHCC) has been reduced across the reef to 5%.

The population of 127 COTS recorded in 1999-00 included a single mature starfish. The existence of significant populations of juvenile (est. age 1) and sub-adult (est. age 2) COTS observed in 1999-00 suggests the possibility of negative impacts on hard coral recovery as a result of the feeding of these cohorts. This suggestion is supported by personal observations that suggest there are significant feeding impacts on newly settled, hard coral recruits. This trend that is likely to persist in the near future.

Figure 3.4. Unnamed Reef (15-070)

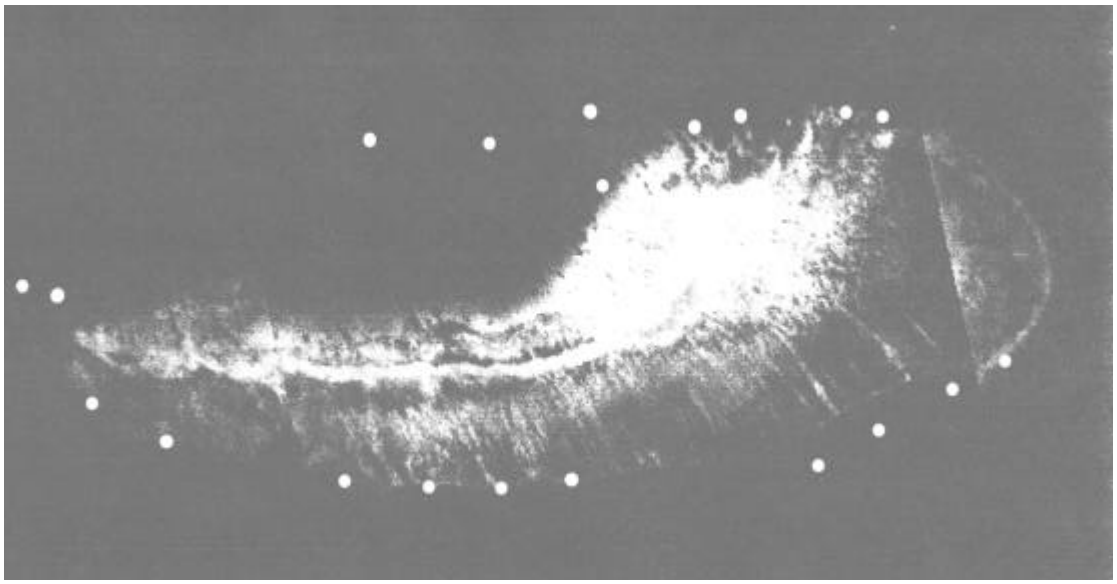


Figure 3.4.1. Aerial photograph of Unnamed Reef (15-070). White dots indicate the approximate locations of the 20 sites surveyed in November 1999.

Table 3.4.a. Reef status classifications for Reef 15-070 since 1994-95.

	Reef Status Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef		ASO	ASO	ASO	ASO	ISO
Front Reef		ISO	NO	NO	FSO	ISO
Entire Reef	NO					IO

Table 3.4.b. Mean densities (±1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1999-00. Values in brackets are total *A. planci* counts.

	Mean Densities (±1SE) (per 250 m^2)		
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**
Back Reef (BR)	0.30±0.11 (6)	0.80±0.24 (16)	0.45±0.11 (9)
Front Reef (FR)	1.35±0.37 (27)	1.45±0.44 (29)	0.25±0.14 (5)
Entire Reef (BR+FR)	0.83±0.21 (33)	1.13±0.25 (45)	0.35±0.09 (14)

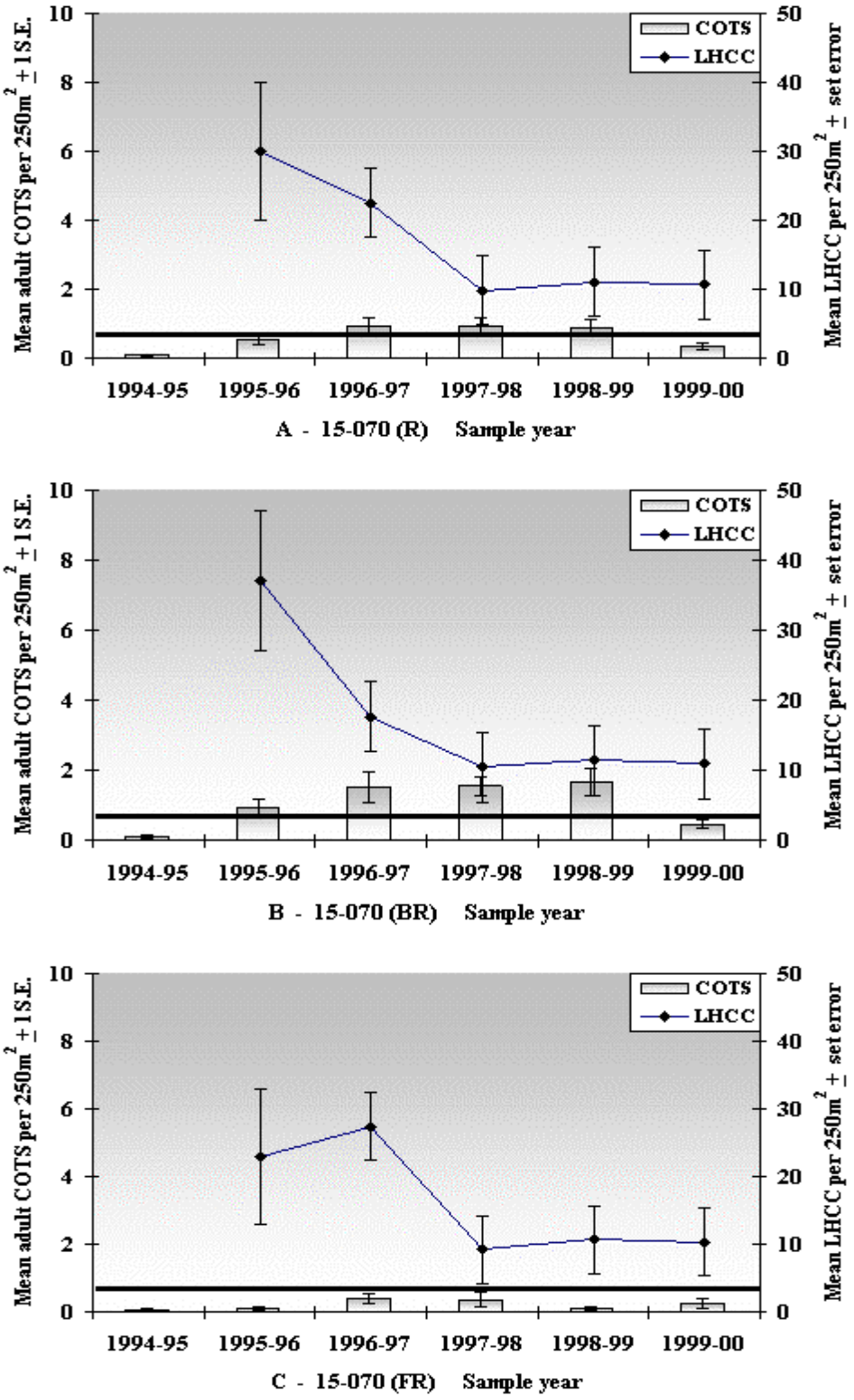


Figure 3.4.2. Reef 15-070. The mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back-reef (B-BR) and front-reef (C-FR) zone. The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbreaking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

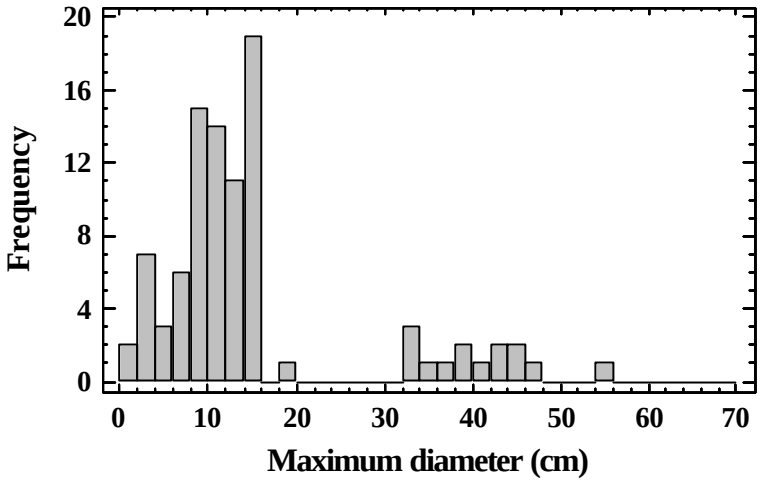


Figure 3.4.3. Size-frequency plots of *A. planci* observed at Reef 15-070 in November 1999.

Summary

The first Active Spot Outbreak (ASO) at Unnamed Reef (15-070) was detected in the reef's back-reef zone in 1995-96. Populations of adult starfish in this zone remained at outbreaking densities for a further three years. During this four-year period, live hard coral cover (LHCC) in the back-reef zone declined from an average of 35% cover to approximately 10%.

Unsustainably high densities of juvenile *A. planci* recorded in 1998-99 suggested the possibility of increase in the densities of sub-adult and adult starfish in the near future. In line with earlier predictions, the 1999-00 surveys detected renewed Incipient Spot Outbreaks (ISO) in both the back- and front-reef zones. If the COTS populations reach active outbreaks status within 12 months, the back-reef zone of 15-070 would have experienced two consecutive outbreaks within two years. In contrast, the front-reef zone experienced above sustainable densities of COTS for the first time in recent years. A further reduction in LHCC across the reef appears likely as the large 1997-98 cohort approaches maturity.

Figure 3.5. Irene Reef (15-084)

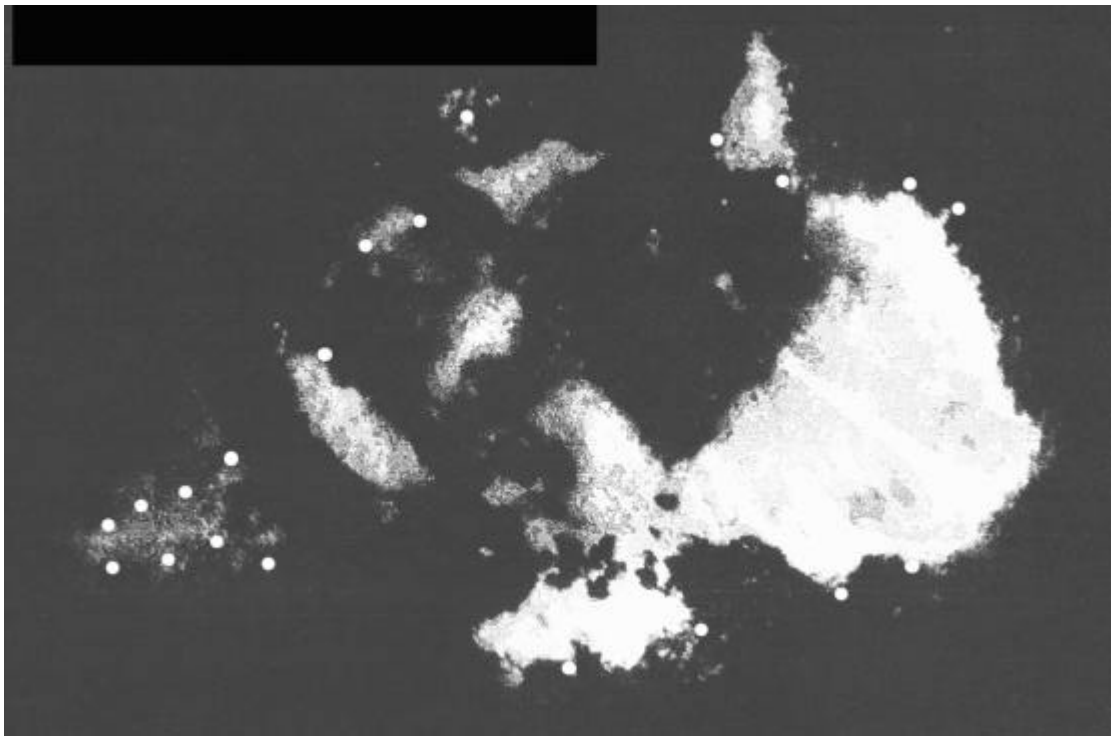


Figure 3.5.1. Aerial photograph of Irene Reef (15-084). White dots indicate the approximate locations of the 20 sites surveyed in November 1999.

Table 3.5.a. Reef status classifications for Reef 15-084 since 1994-95

	Reef Status Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef	ASO	ASO	ASO	ASO	PSO	PSO
Front Reef	NO	ISO	NO	NO	FSO	ISO
Entire Reef						

Table 3.5.b. Mean densities (±1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1999-00. Values in brackets are total *A. planci* counts.

	Mean Densities (±1SE) (per 250 m^2)		
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**
Back Reef (BR)	0.35±0.25 (7)	0.40±0.15 (8)	0.15±0.08 (3)
Front Reef (FR)	3.70±0.97 (74)	3.80±0.94 (76)	0.00±0.00 (0)
Entire Reef (BR+FR)	2.03±0.56 (81)	2.10±0.54 (84)	0.08±0.04 (3)

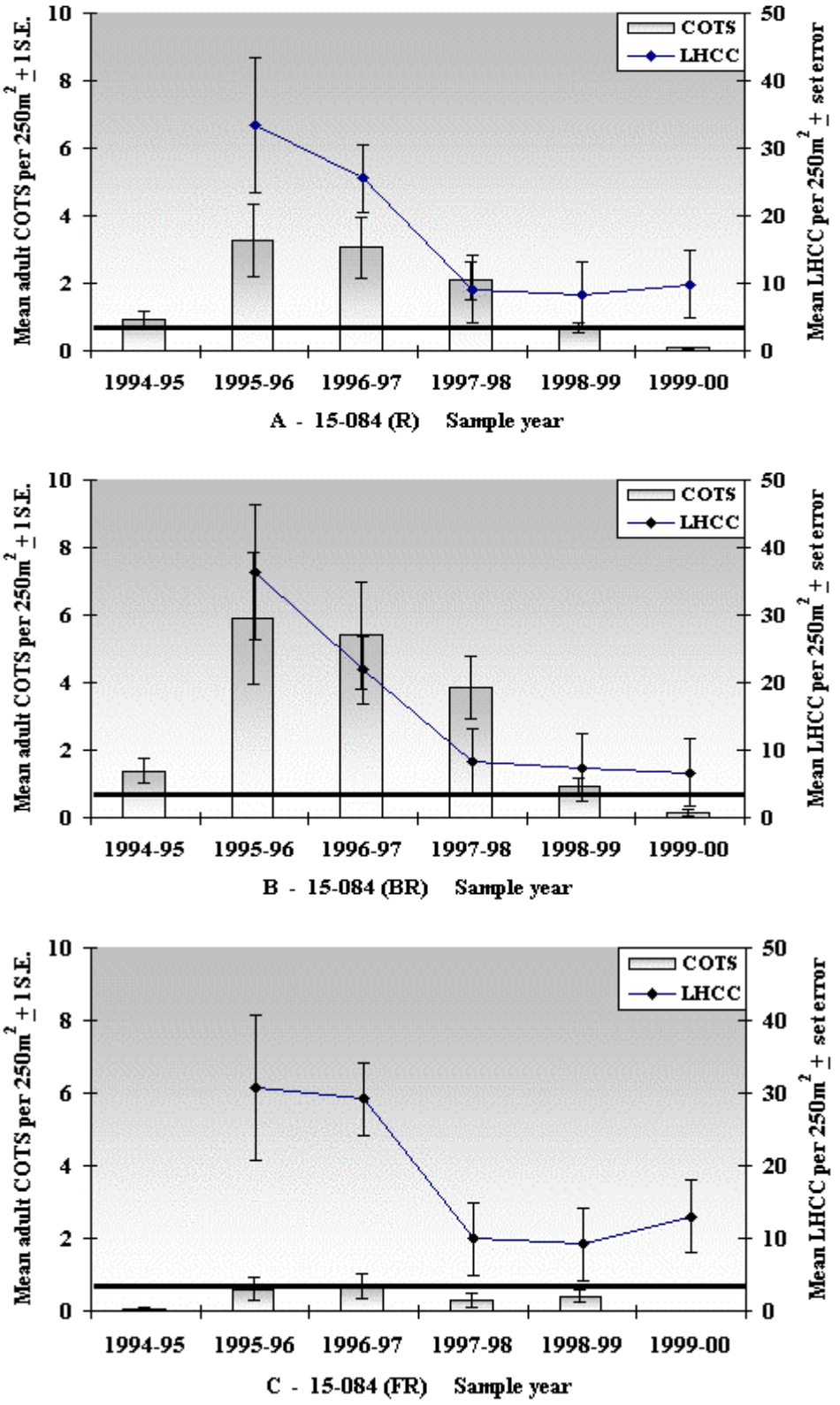


Figure 3.5.2. Reef 15-084. The mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back-reef zone (B-BR) and in the front-reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable,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

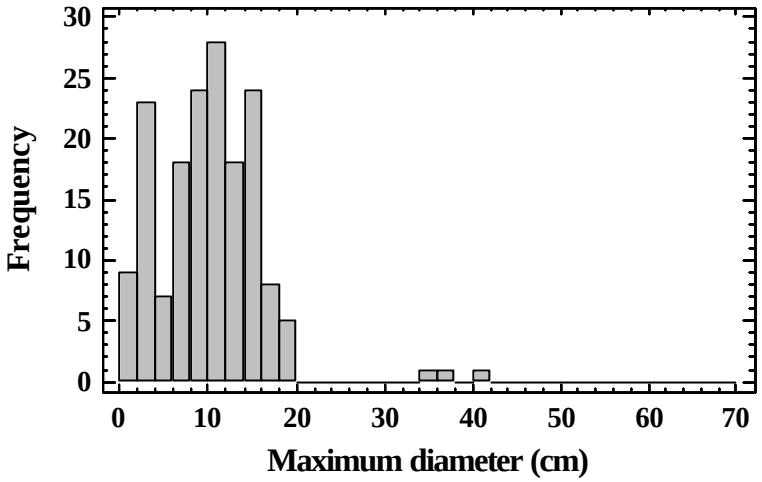


Figure 3.5.3. Size-frequency plots of *A. planci* observed at Reef 15-084 in November 1999.

Summary

The Active Spot Outbreak (ASO) discovered in the back-reef zone at Irene Reef (15-084) in 1994-95 remained at, or near, outbreaking densities for five consecutive years. However, the 1999-00 surveys found the previous adult population in this reef zone had almost totally collapsed. This trend was not unexpected because live hard coral cover (LHCC) in the back-reef zone has declined from an average of 35-40% to around 5% . Consequently, the back-reef zone at Irene Reef continues to be classified as a Post Spot Outbreak (PSO).

Unsustainably high densities of juvenile *A. planci* recorded in 1998-99 suggested that starfish numbers at Irene Reef would increase. The exposed front-reef zone was identified as a likely Future Spot Outbreak (FSO) following last year's surveys. In line with our projections, a high density population of sub-adult starfish was recorded in the front-reef zone during the 1999-00 survey. As a result, this zone has been reclassified to the status of Incipient Spot Outbreak (ISO). Increasing feeding activities of the 1997-98 cohort are likely to significantly reduce the LHCC from its current level of 15%.

Figure 3.6. Evening Reef (15-095)

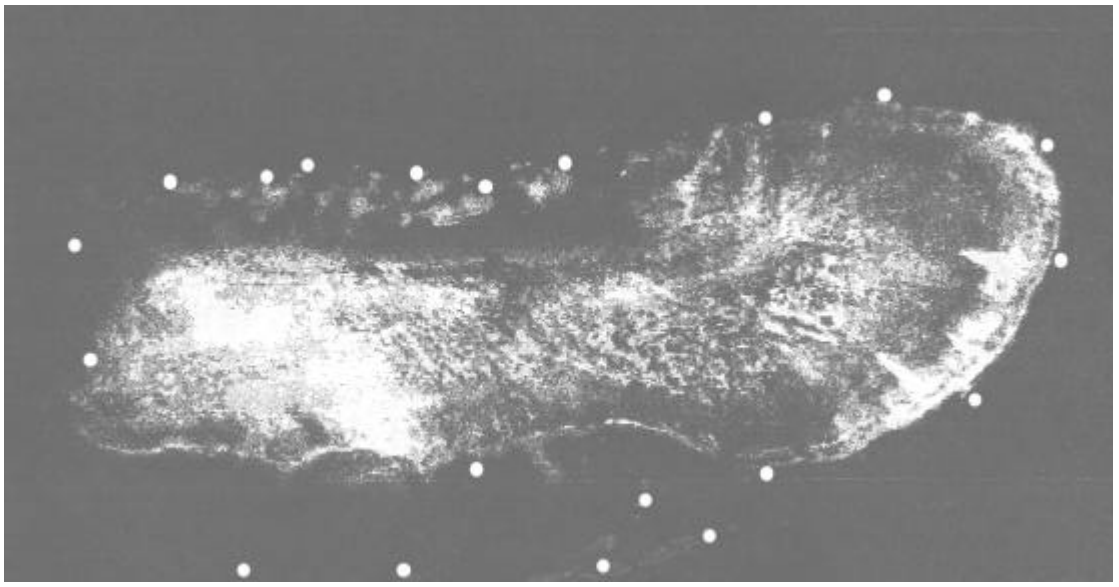


Figure 3.6.1. Aerial photograph of Evening Reef (15-095). White dots indicating the approximate locations of the 20 sites surveyed in November 1999.

Table 3.6.a. Reef status classifications for Reef 15-095 since 1994-95

	Reef Status Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef	ASO	ASO	ASO	PSO	PSO	PSO
Front Reef	NO	ISO	NO	NO	NO	ISO
Entire Reef						

Table 3.6.b. Mean densities (? 1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1999-00. Values in brackets are total *A. planci* counts.

	Mean Densities (±1SE) (per 250 m^2)		
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**
Back Reef (BR)	0.30±0.11 (6)	0.35±0.15 (16)	0.25±0.12 (5)
Front Reef (FR)	1.30±0.32 (26)	1.25±0.40 (15)	0.00±0.00 (0)
Entire Reef (BR+FR)	0.80±0.18 (32)	0.80±0.22 (32)	0.13±0.06 (5)

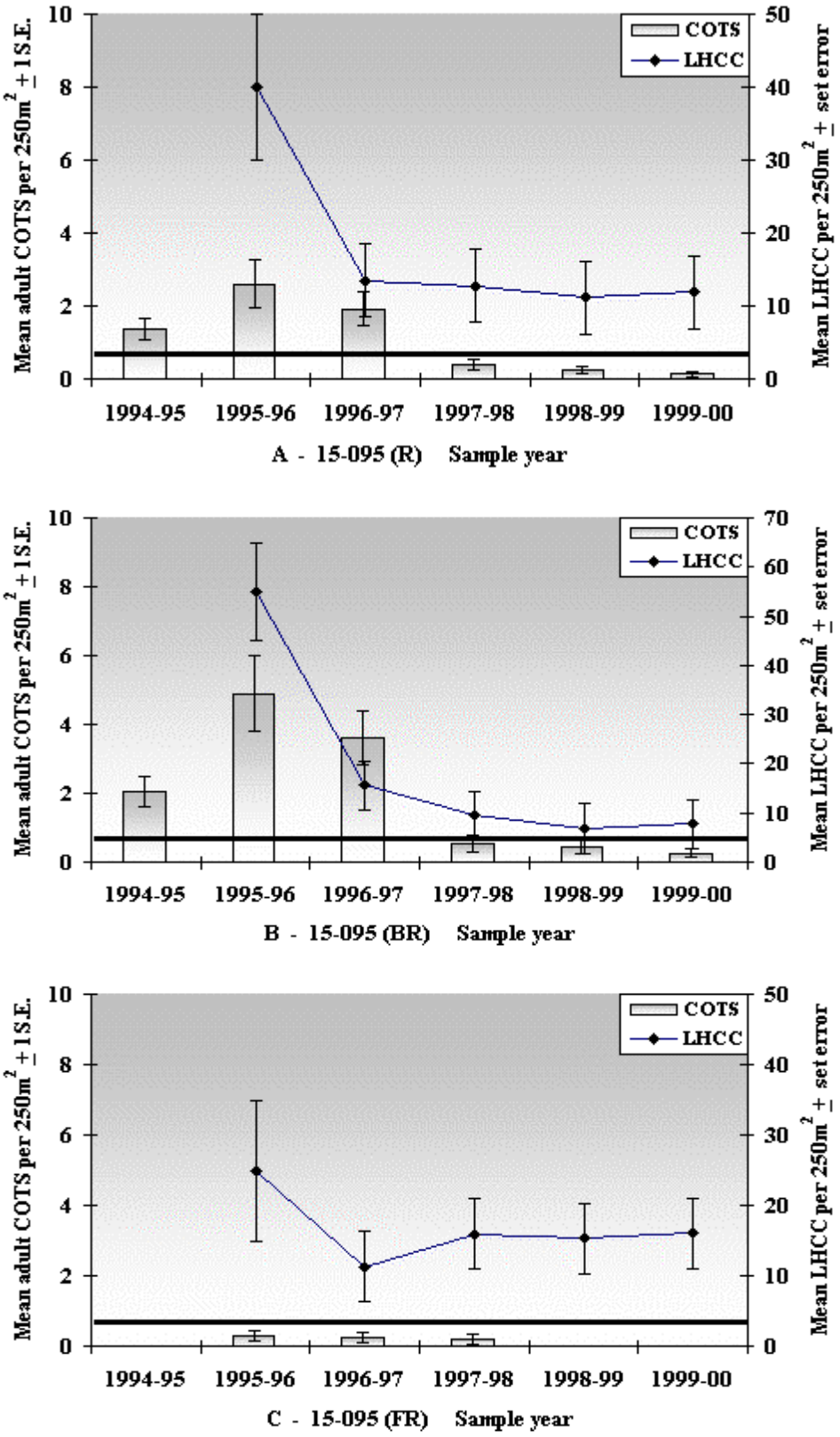


Figure 3.6.2. Reef 15-095. The mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back-reef zone (B-BR) and in the front-reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable,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

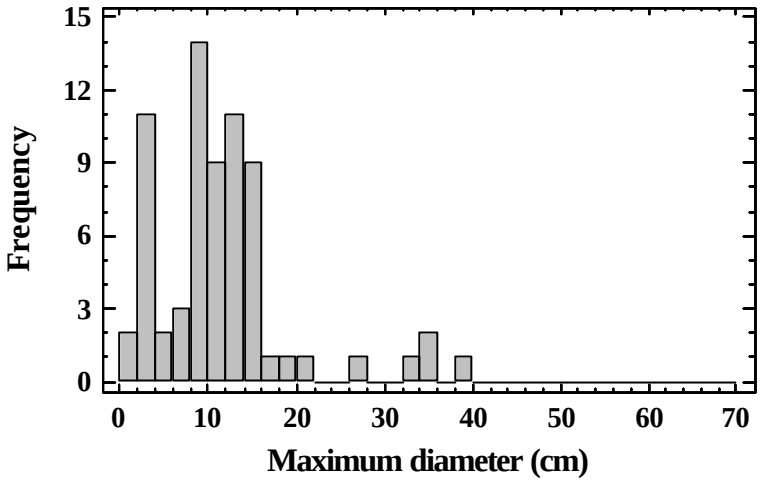


Figure 3.6.3. Size-frequency plots of *A. planci* observed at Reef 15-095 in November 1999.

Summary

The Active Spot Outbreak (ASO) discovered in the back-reef zone at Evening Reef (15-095) in 1994-95 remained at outbreaking densities for three consecutive years. Consequently, live hard coral cover (LHCC) in the back-reef zone declined from an average of 50-60% cover to less than 10%. LHCC in the back-reef zone has remained low and is showing little sign of recovery. Remnant populations of hard corals are almost exclusively dominated by massive *Porites* spp., the branching coral *Acropora brueggemanni* and isolated stands of *Porites cylindrica*.

The detection of juvenile *A. planci* in 1998-99 suggested that starfish numbers would increase in the near future. The exposed front-reef zone was most likely to be affected by the 1997-98 cohort of *A. planci.* Following the latest surveys in 1999-00, the front-reef zone of Evening Reef is classified as an Incipient Spot Outbreak (ISO) suggesting that above sustainable densities of adult COTS will appear during 2000-01.

Figure 3.7. Rudder Reef (16-023)

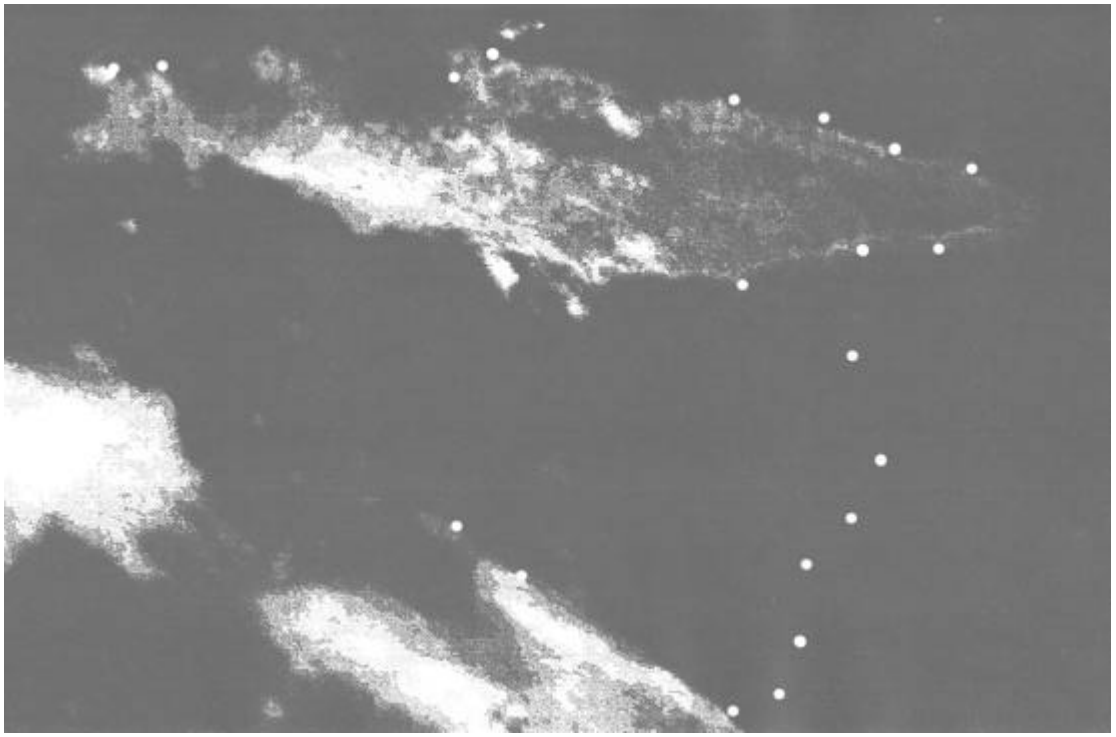


Figure 3.7.1. Aerial photograph of Rudder Reef (east) (16-023). White dots indicating the approximate locations of the 20 sites surveyed in December 1999.

Table 3.7.a. Reef status classifications for Reef 16-023 since 1994-95

	Reef Status Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef				ASO	ASO	PSO
Front Reef				PSO	FSO	ISO
Entire Reef	NO	IO	AO			

Table 3.7.b. Mean densities (±1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1999-00. Values in brackets are total *A. planci* counts.

	Mean Densities (±1SE) (per 250 m^2)		
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**
Back Reef (BR)	1.20±0.32 (24)	0.85±0.41 (17)	0.10±0.07 (2)
Front Reef (FR)	5.05±0.84 (101)	5.90±1.01 (118)	0.85±0.41 (17)
Entire Reef (BR+FR)	3.13±0.54 (125)	3.38±0.67 (135)	0.48±0.21 (19)

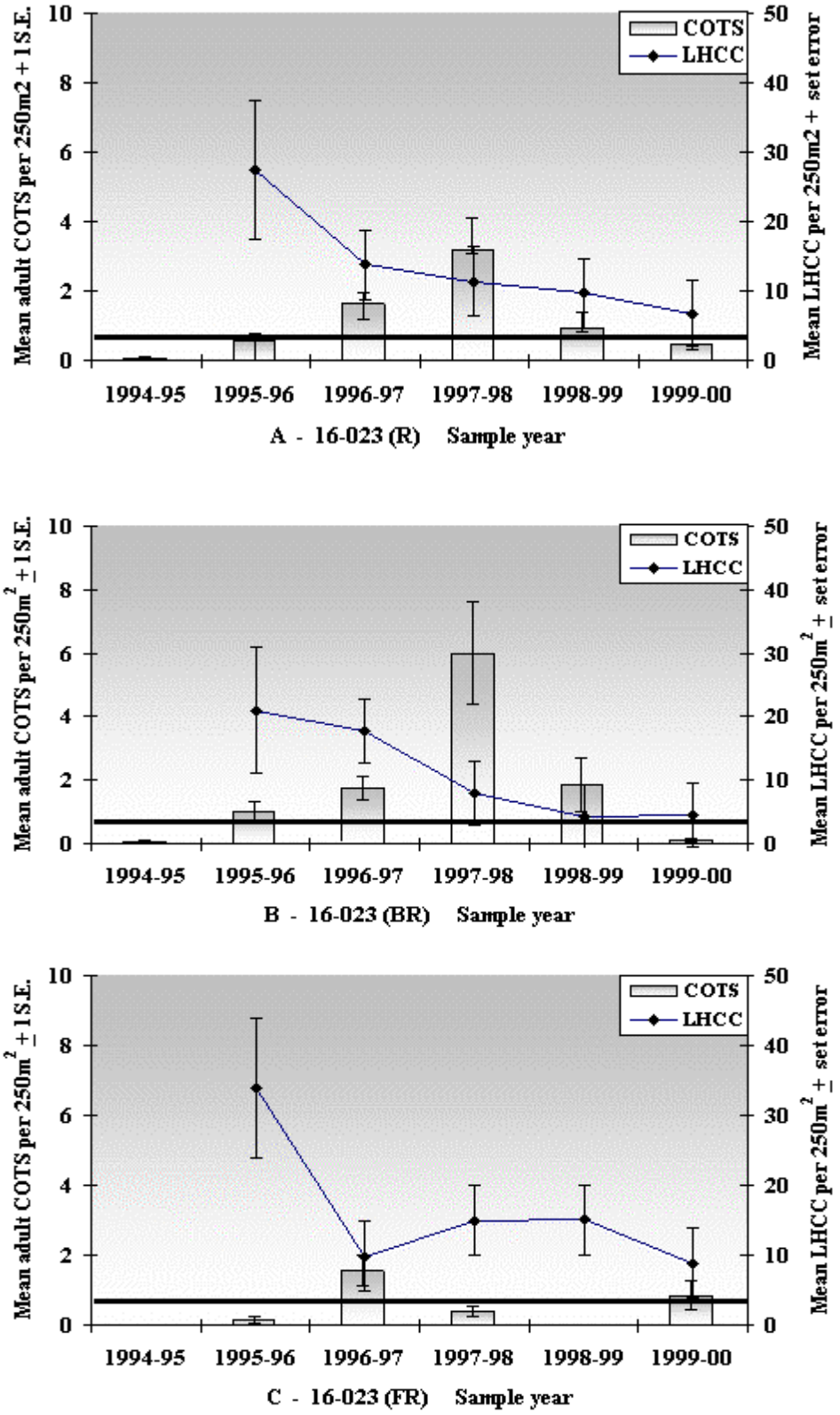


Figure 3.7.2. Reef 16-023. The mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back-reef zone (B-BR) and in the front-reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable,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

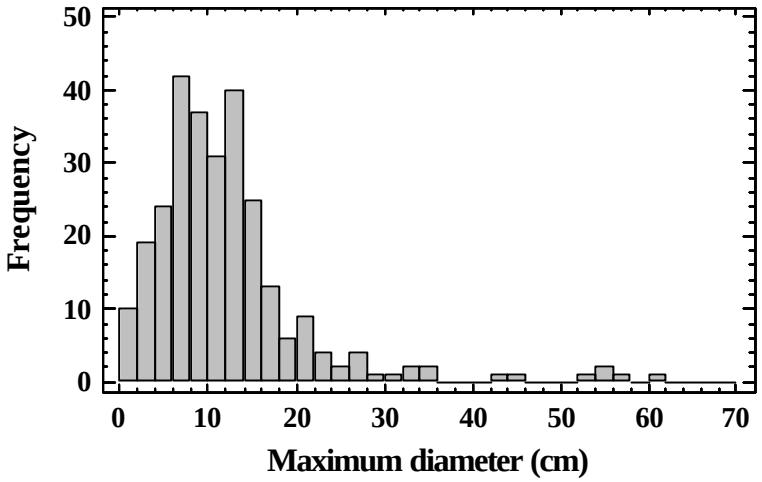


Figure 3.7.3. Size-frequency plots of *A. planci* observed at Reef 16-023 in December 1999.

Summary

Rudder Reef (16-023) was classified as an Incipient Outbreak (IO) in 1995-96. As predicted, an Active Outbreak (AO) developed during the following 12 months. The outbreaking population in the back-reef zone remained at above sustainable densities for three consecutive years. During this period, live hard coral cover (LHCC) in the back-reef zone declined from an average of 20-25% to about 5%. During the last two years, LHCC in this reef zone has not shown any significant signs of recovery.

In contrast, the outbreaking population detected in the front-reef zone in 1996-97 only persisted for one year. However, the observed spot outbreak in this zone caused the marked reduction in LHCC from about 35% to a remnant coral cover of around 10%. There was a slight increase in LHCC in the front-reef area between late 1997 and early 1999 which is currently being affected by renewed COTS feeding activity. Unsustainably high numbers of juvenile *A. planci* were recorded in this zone in 1998-99 which suggests that adult starfish densities will increase. The front-reef zone was classified as a Future Spot Outbreak (FSO) following last year's surveys. In line with our predictions, above-sustainable densities of sub-adult starfish were recorded in 1999-00. Therefore, the front-reef zone's status was upgraded to Incipient Spot Outbreaks (ISO). The outbreak that is likely to develop in this reef zone, three to four years after the previous event, suggests that LHCC will be further reduced in the near future.

Figure 3.8. Unnamed Reef (16-024)

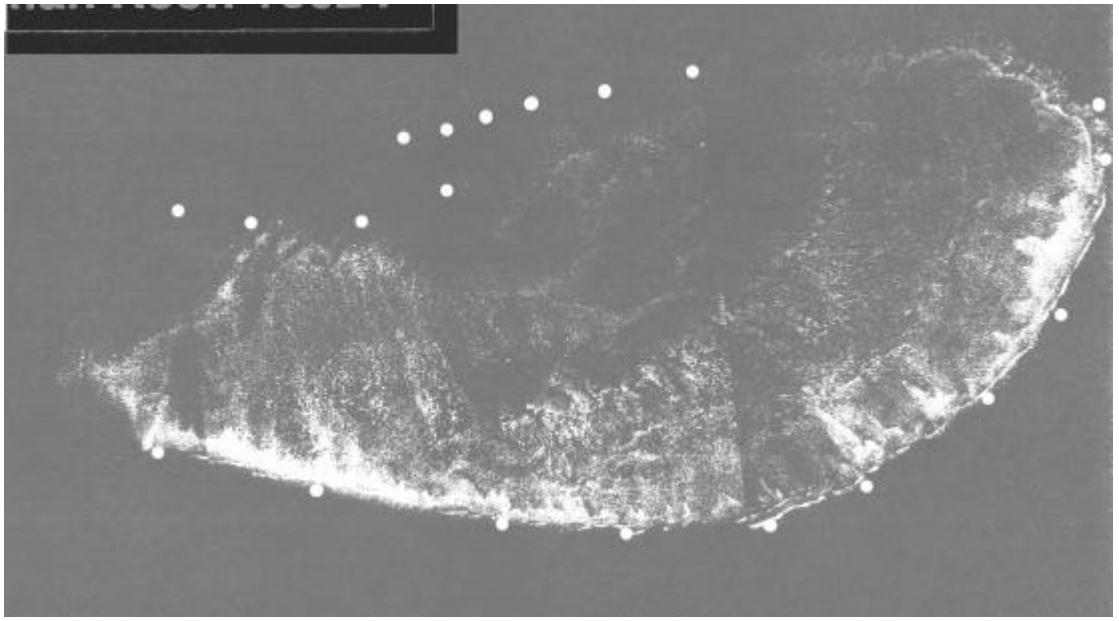


Figure 3.8.1. Aerial photograph of Unnamed Reef (16-024). White dots indicate the approximate locations of the 20 sites surveyed in December 1999.

Table 3.8.a Reef status classifications for Reef 16-024 since 1994-95

	Reef Status Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef					PSO	PSO
Front Reef					FSO	PSO
Entire Reef	NO	IO	AO	AO		PO

Table 3.8.b. Mean densities (±1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1999-00. Values in brackets are total *A. planci* counts.

	Mean Densities (±1SE) (per 250 m^2)		
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**
Back Reef (BR)	0.00±0.00 (0)	0.00±0.00 (0)	0.00±0.00 (0)
Front Reef (FR)	1.50±0.34 (30)	0.25±0.16 (5)	0.00±0.00 (0)
Entire Reef (BR+FR)	0.75±0.21 (30)	0.13±0.08 (5)	0.00±0.00 (0)

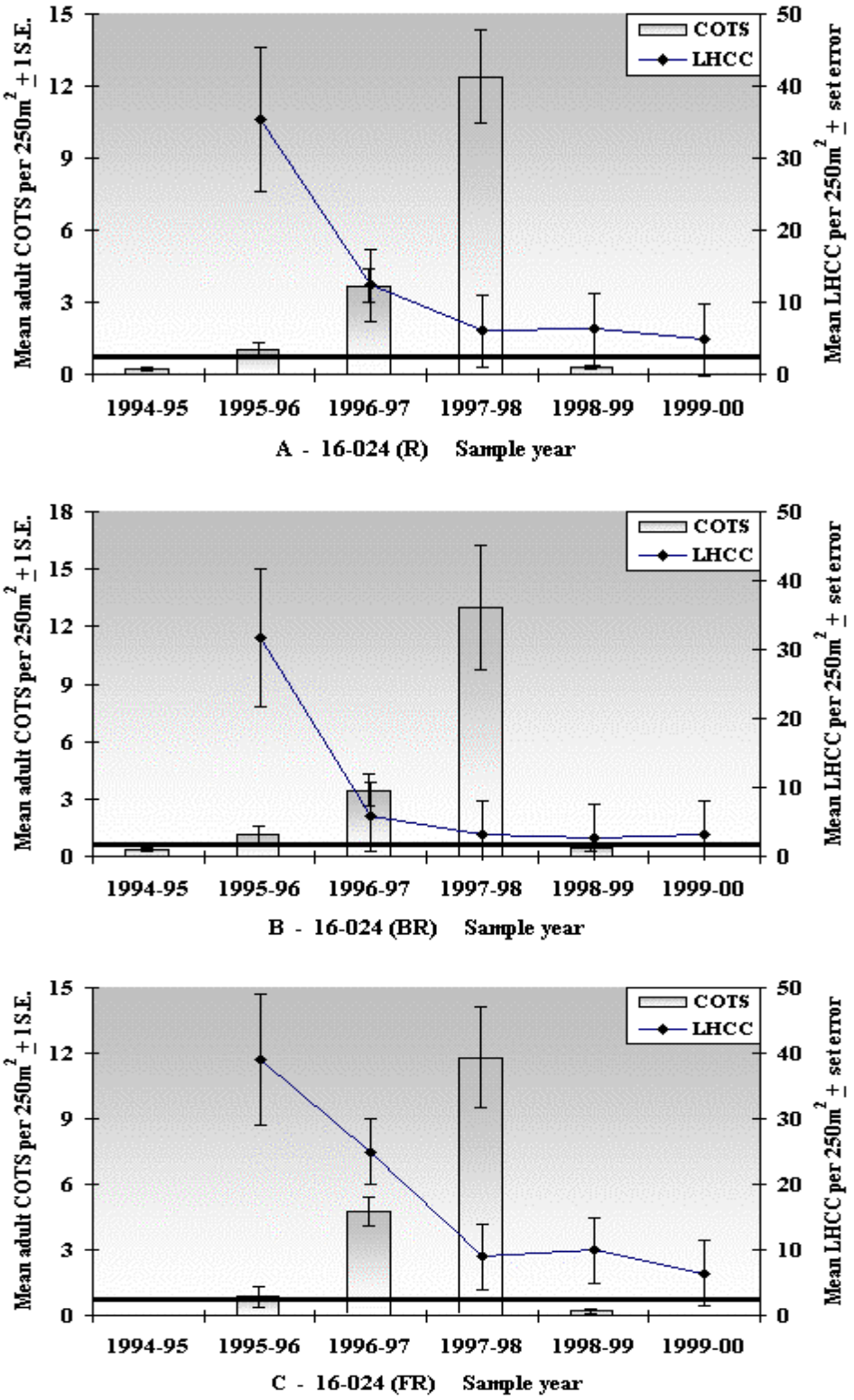


Figure 3.8.2. Reef 16-024. The mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back-reef zone (B-BR) and in the front-reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable,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

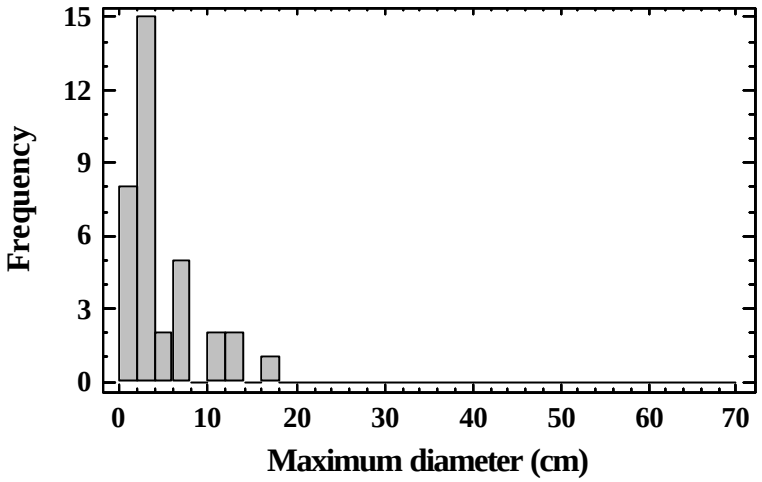


Figure 3.8.3. Size-frequency plots of *A. planci* observed at Reef 16-024 in December 1999.

Summary

Unnamed Reef (16-024) was classified as an Incipient Outbreak (IO) in 1995-96. As predicted, an Active Outbreak (AO) developed during the following 12 months. Adult starfish populations in both the back- and front-reef zone remained at outbreaking densities for the following two years. At the outbreak's peak in 1997-98, adult densities were recorded at approximately 16-times sustainable levels. During this two-year period, live hard coral cover (LHCC) declined from an average of 35% across the reef to 5-10%. The 1999-00 surveys did not detect any significant hard coral recovery with LHCC in both the back-reef and front-reef zones at about 5%.

The unsustainably high densities of juvenile *A. planci* recorded in the front-reef zone in 1998-99 have not translated into a significant sub-adult population of starfish. However, as LHCC in this zone has declined, it is possible that the 1997-98 cohort affected local LHCC before largely disappearing.

Figure 3.9. Thetford Reef (16-068)

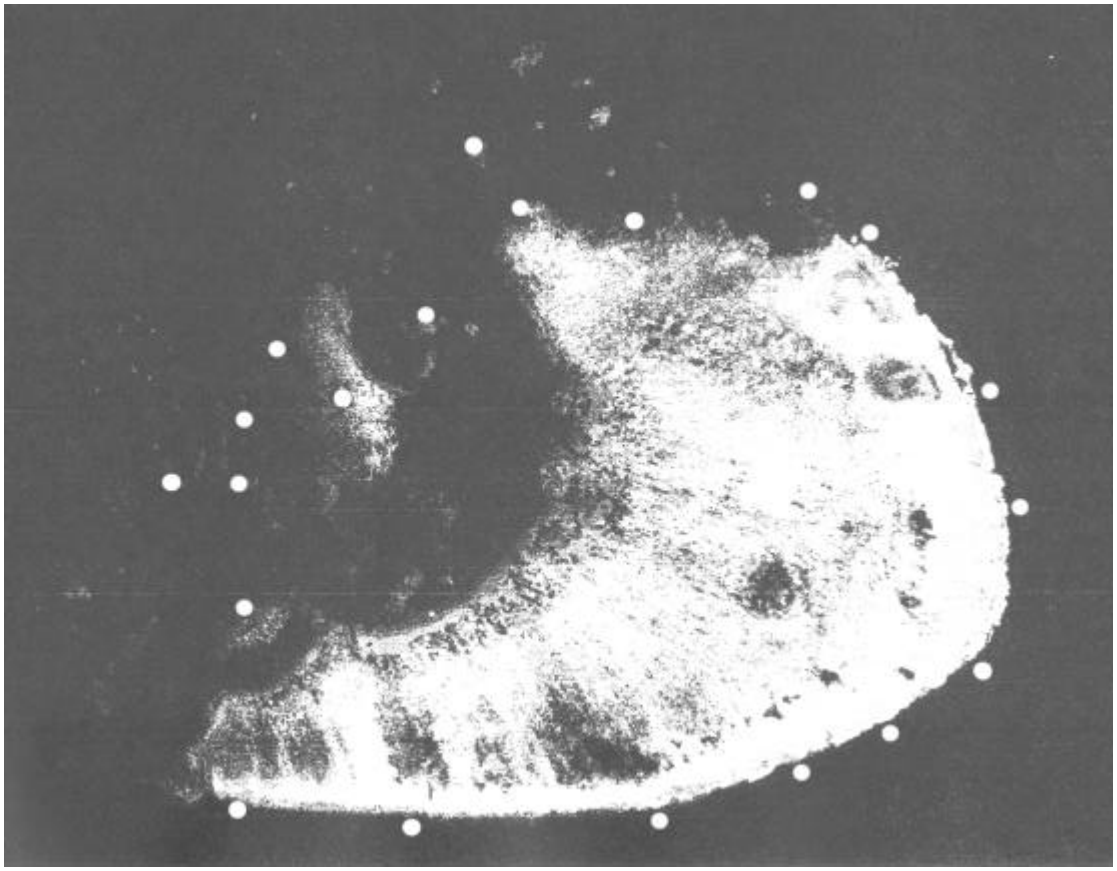


Figure 3.9.1. Aerial photograph of Thetford Reef (16-068). White dots indicate the approximate locations of the 20 sites surveyed in December 1999.

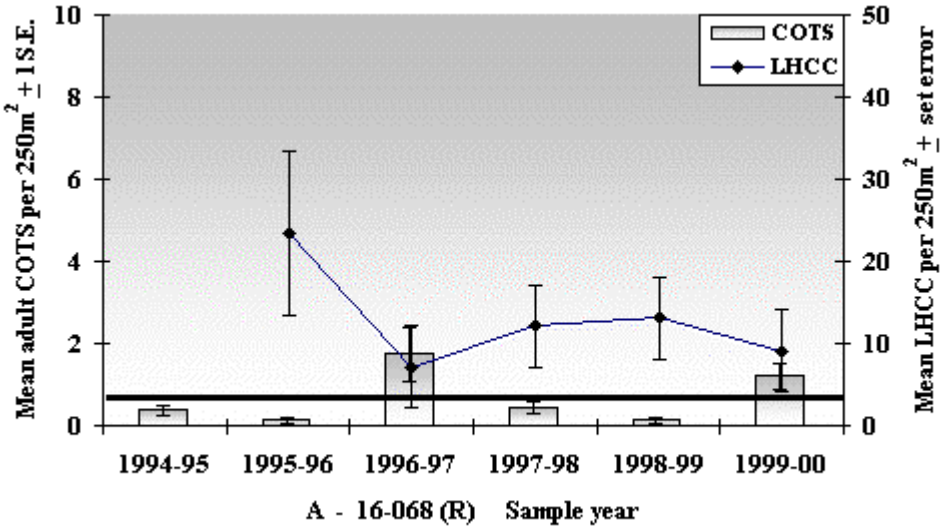
Table 3.9.a. Reef status classifications for Reef 16-068 since 1994-95

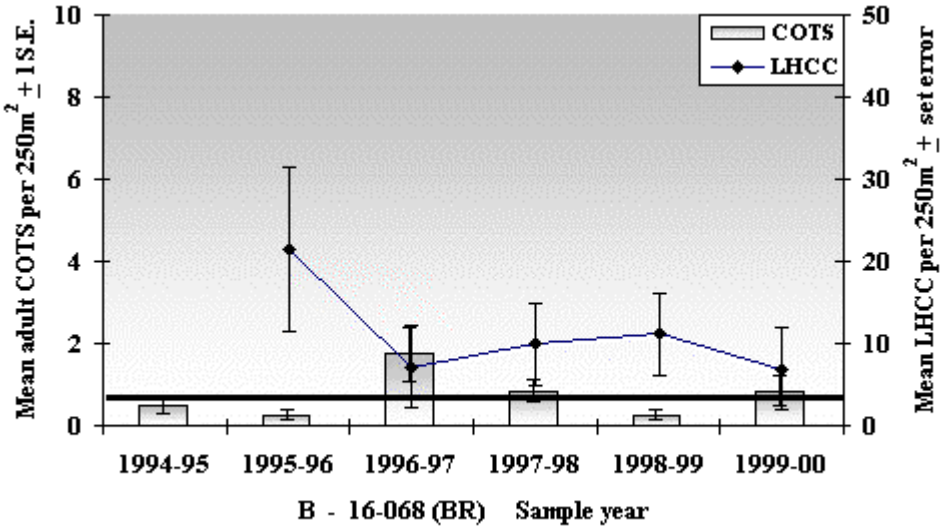
	Reef Staus Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef	NO	NO	ASO	PSO	PSO	ISO
Front Reef			NS	NO	FSO	ASO
Entire Reef						

Table 3.9.b. Mean densities (±1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1999-00. Values in brackets are total *A. planci* counts.

	Mean Densities (±1SE) (per 250 m^2)		
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**
Back Reef (BR)	0.40±0.13 (8)	7.40±2.57 (148)	0.85±0.35 (17)

Front Reef (FR)	1.55±0.33 (31)	12.90±2.11 (258)	1.55±0.56 (31)
Entire Reef (BR+FR)	0.98±0.20 (39)	10.15±1.70 (406)	1.20±0.33 (48)





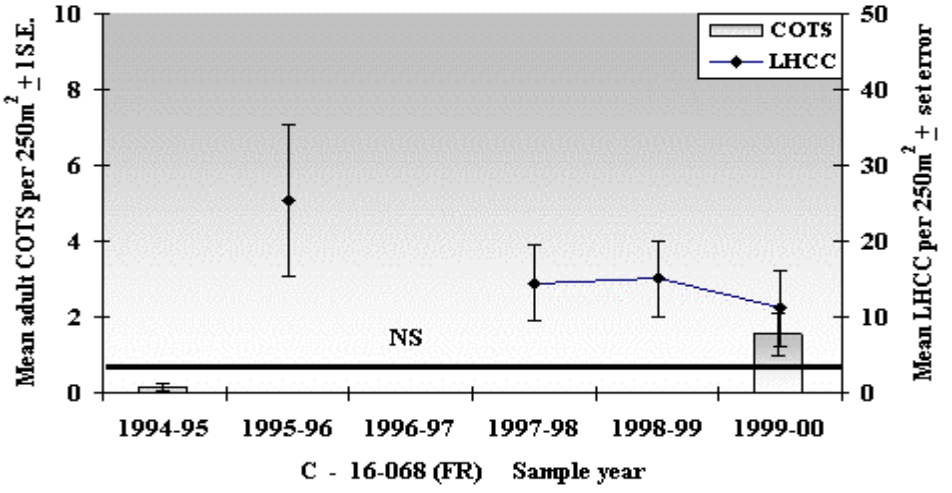


Figure 3.9.2. Reef 16-068. The mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back-reef zone (B-BR) and in the front-reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable,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

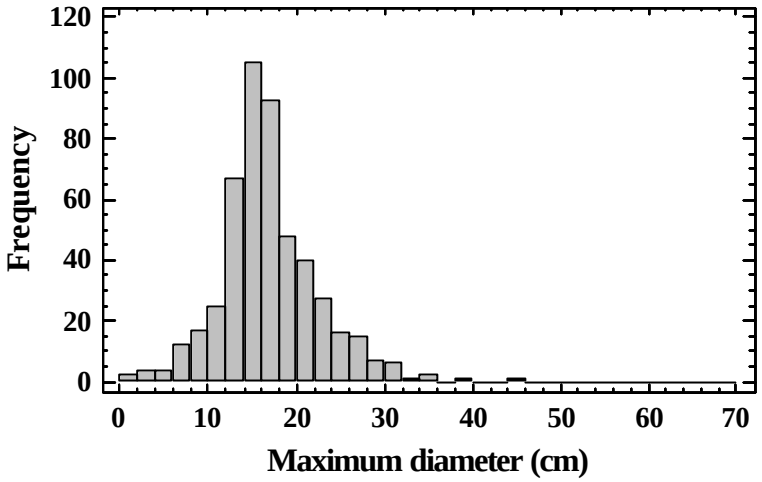


Figure 3.9.3. Size-frequency plots of *A. planci* observed at Reef 16-068 in December 1999.

Summary

The first signs of locally unsustainable *A. planci* densities at Thetford Reef (16-068) were detected in 1996-97. However, the Active Spot Outbreak (ASO) identified in the back-reef zone did not remain at outbreaking levels. By 1997-98, starfish densities had declined to below outbreaking levels. The 1998-99 surveys recorded significant and unsustainably high densities of juvenile *A. planci* in the back- and front-reef zone, respectively. Consequently, the front-reef zone was classified as a Future Spot Outbreak (FSO).

It appears that the predicted FSO in the front-reef zone has matured faster than anticipated. The 1999-00 surveys recorded an Active Spot Outbreak (ASO) in the front-reef zone. Densities of sub-adult COTS in both reef zones are unsustainably high and are likely to experience outbreaking densities of adult starfish. The outbreak in the back-reef zone is likely to develop only four years after the previous event that significantly reduced live hard coral cover (LHCC) from above 20% to below 10%. Further significant losses of LHCC are likely to affect Thetford Reef in the near future.

Figure 3.10. Scott Reef (17-004)

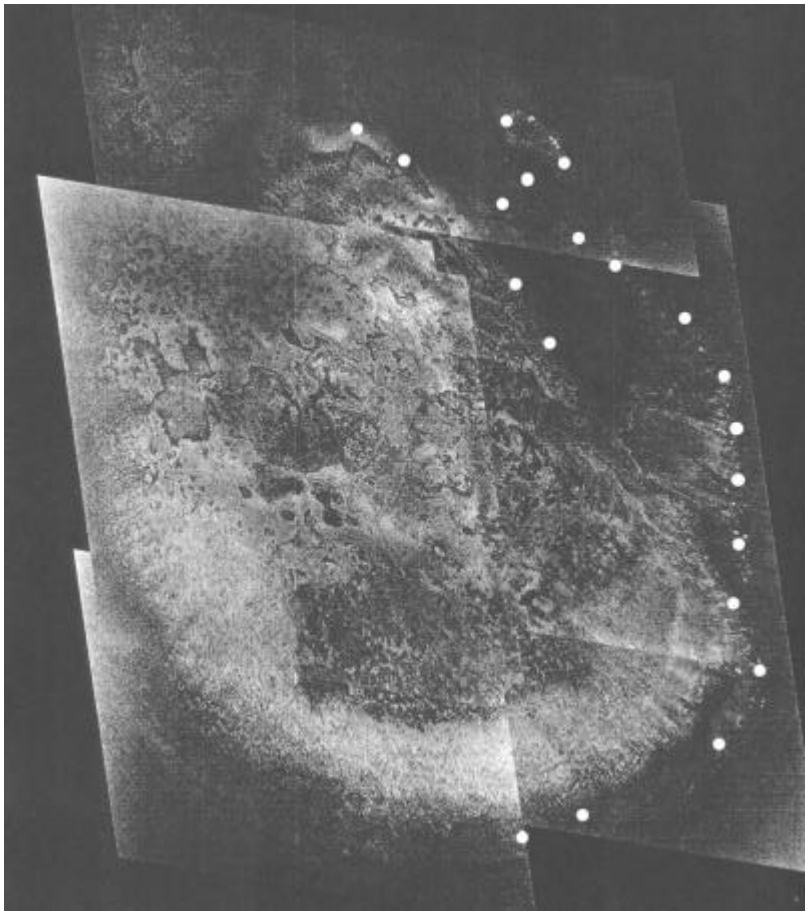


Figure 3.10.1. Aerial photograph of Scott Reef (17-004). White dots indicate the approximate locations of the 20 sites surveyed in February and April 2000.

Table 3.10.a. Reef status classification for Reef 17-004 since 1994-95.

	Reef Status Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef		ISO	ASO	ASO	ASO	PSO
Front Reef	NS	NO	NO	ISO	FSO	ISO
Entire Reef	NS					

Table 3.10.b. Mean densities (±1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1999-00. Values in brackets are total *A. planci* counts.

	Mean Densities (±1SE) (per 250 m^2)		
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**
Back Reef (BR)	1.00±0.42	0.05±0.05	0.00±0.00

	(20)	(1)	(0)
Front Reef (FR)	2.55±0.67 (51)	1.00±0.25 (20)	0.20±0.12 (4)
Entire Reef (BR+FR)	1.78±0.41 (71)	0.53±0.15 (21)	0.10±0.06 (4)

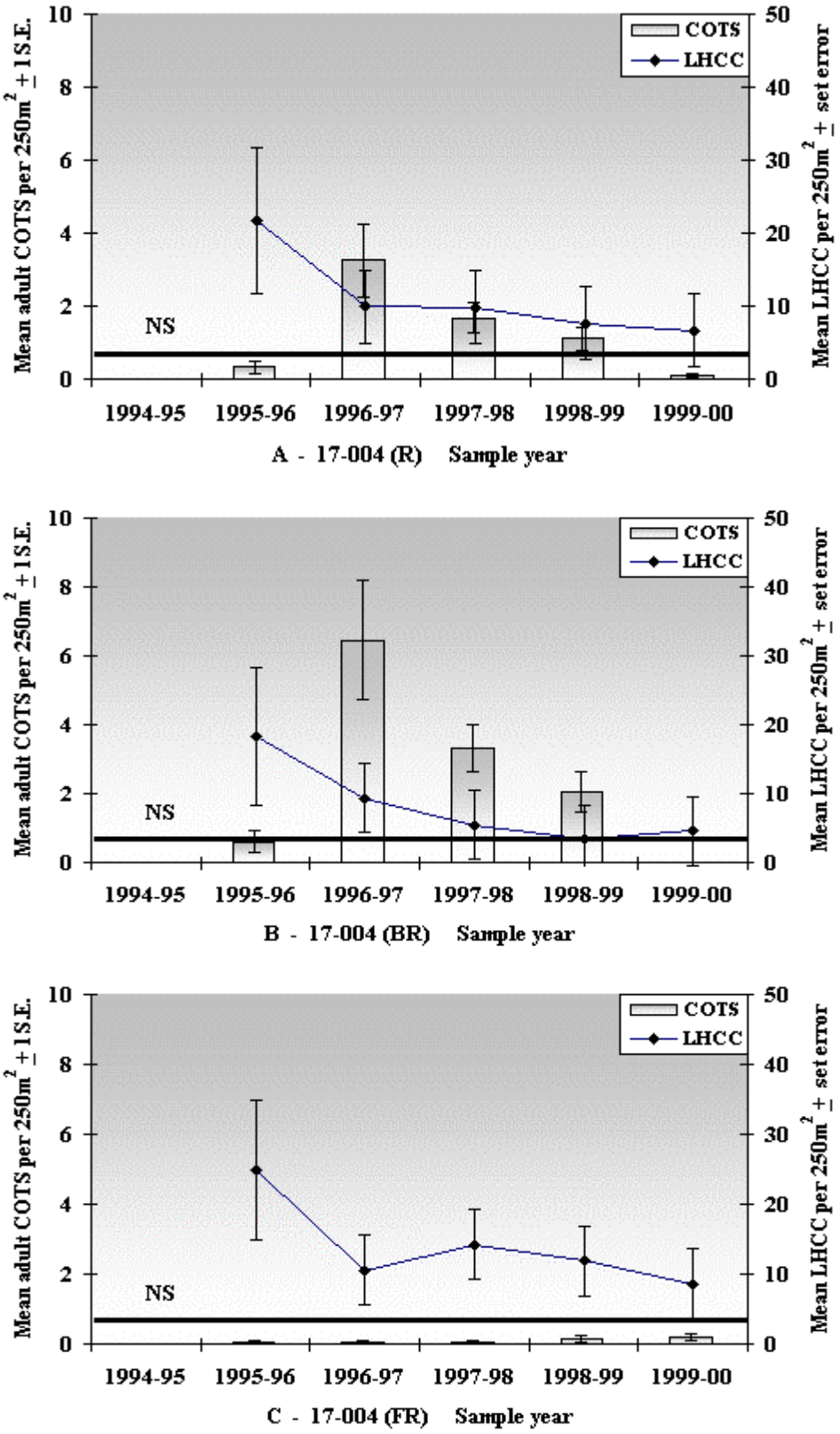


Figure 3.10.2. Reef 17-004. The mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back-reef zone (B-BR) and in the front-reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbreaking population.

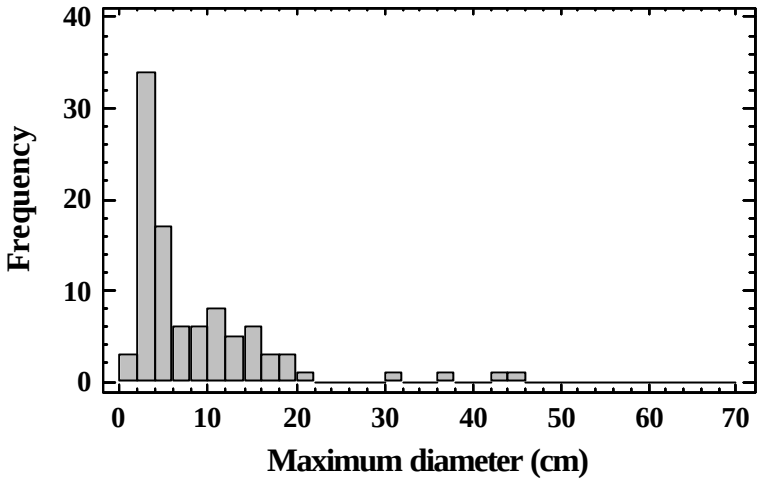


Figure 3.10.3. Size-frequency plot of *A. planci* observed at Reef 17-004 in February and April 2000.

Summary

The first signs of increasing *A. planci* activity at Scott Reef (17-004) were detected in 1995-96 when an Incipient Spot Outbreak (ISO) was identified in the back-reef zone. As predicted, an Active Spot Outbreak (ASO) developed in this zone in 1996-97. The ASO persisted for three years during which live hard coral cover (LHCC) declined from 20% to below 5% in 1998-99. The outbreaking population in this zone had completely collapsed and no adult starfish were recorded in 1999-00. LHCC remains at around 5% with few indications of any significant hard coral recovery.

Densities of sub-adult and adult starfish are increasing gradually. The unsustainably high densities of juvenile starfish recorded in the front-reef zone of Scott Reef in 1998-99 led to its classification as a Future Spot Outbreak (FSO). In line with our prediction, densities of sub-adult and adult COTS have reached levels that warrant a re-classification of this zone to Incipient Spot Outbreak (ISO). Already, the LHCC at the front-reef zone is declining as a result of COTS feeding activities. A further reduction in LHCC is expected as the 1997-98 cohort of *A. planci* approaches maturity.

Figure 3.11. Coates Reef (17-011)

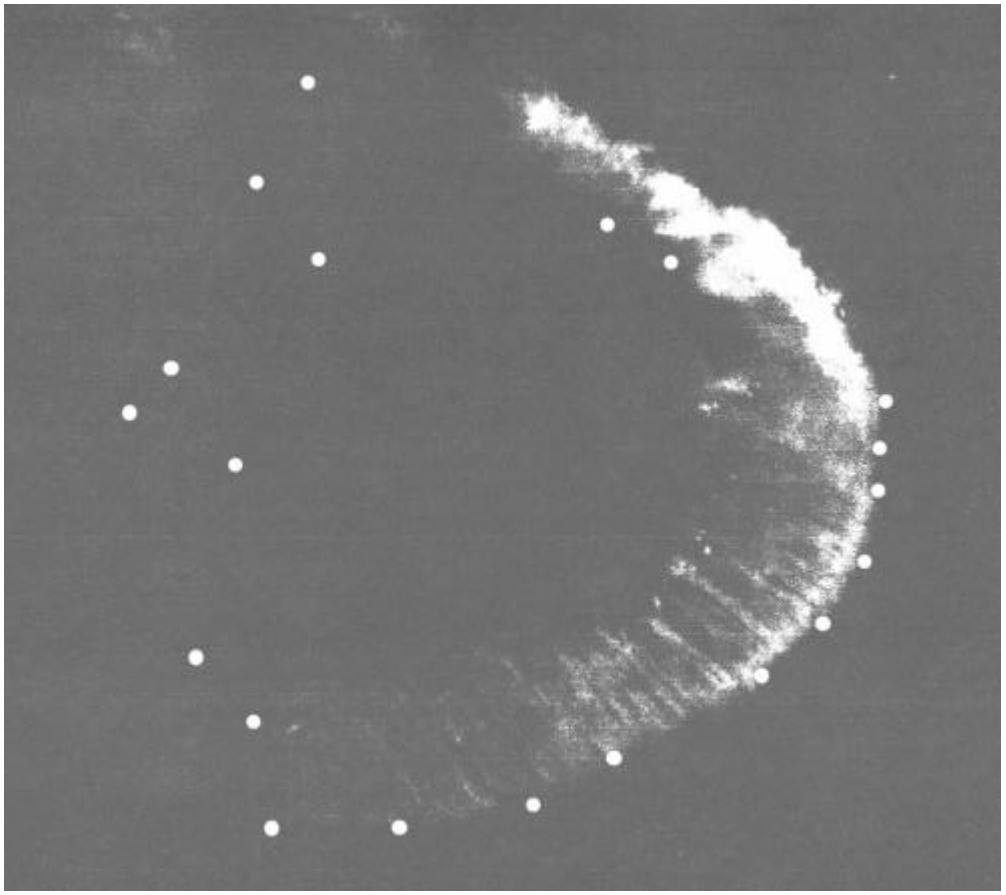


Figure 3.11.1. Aerial photograph of Coates Reef (17-011). White dots indicate the approximate locations of the 20 sites surveyed in February and March 2000.

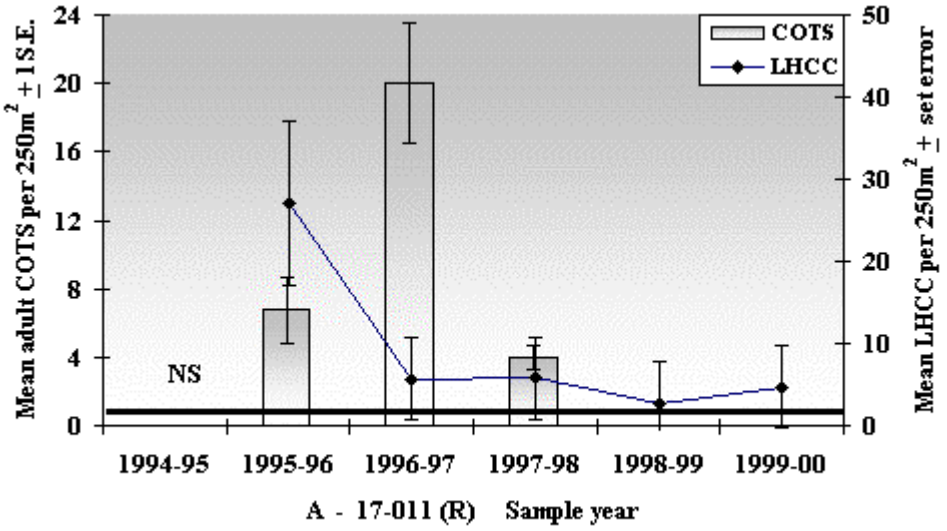
Table 3.11.a. Reef status classification for Reef 17-011 since 1994-95.

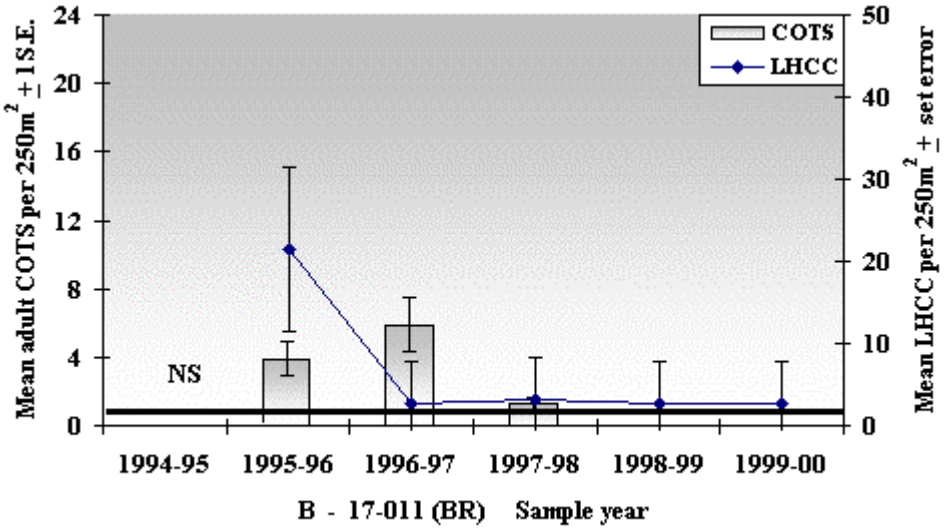
	Reef Status Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef	NS				PSO	PSO
Front Reef					NS	PSO
Entire Reef		AO	AO	AO		PO

Table 3.11.b. Mean densities (±1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1999-00. Values in brackets are total *A. planci* counts.

	Mean Densities (±1SE) (per 250 m^2)		
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**
Back Reef (BR)	0.30±0.13	0.05±0.05	0.00±0.00

	(6)	(1)	(0)
Front Reef (FR)	1.90±0.38 (38)	0.00±0.00 (0)	0.00±0.00 (0)
Entire Reef (BR+FR)	1.10±0.23 (44)	0.03±0.03 (1)	0.00±0.00 (0)





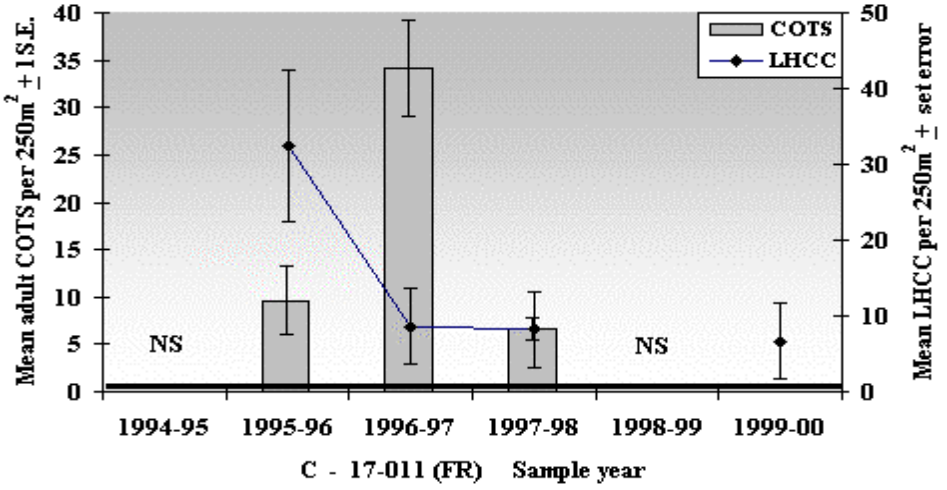


Figure 3.11.2. Reef 17-011. Trends in the mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back-reef zone (B-BR) and in the front-reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbreaking population.

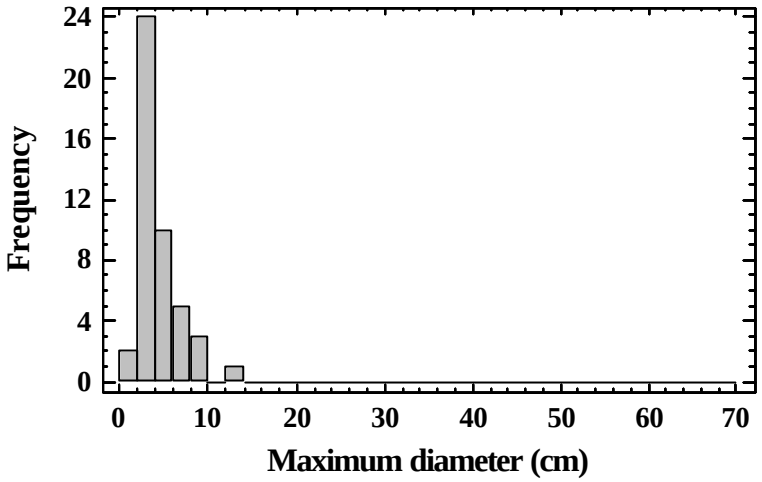


Figure 3.11.3. Size-frequency plot of *A. planci* observed at Reef 17-011 in February and March 2000.

Summary

When first surveyed in 1995-96, Coates Reef (17-011) supported an Active reef-wide Outbreak (AO). In 1996-97, outbreaking densities of adult COTS across the reef peaked at around 26-times sustainable numbers with the front-reef zone experiencing densities some 46-times above the threshold level. The outbreak continued for three years until 1997-98 when adult starfish populations in both the back- and front-reef zone started to decline rapidly. During this period, live hard coral cover (LHCC) in the back-reef zone was reduced from an average of 20-25% to below 5%. The reduction in LHCC was more significant in the front-reef zone where coral cover declined from pre-outbreak levels of around 35% mean cover to below 10%.

For the last two years, LHCC in both the back- and front-reef zones has remained unchanged at approximately 0-5% and 5-10%, respectively. In 1998-99 and 1999-00, we observed little indication of any significant coral recovery. Coates Reef remains classified as Post Outbreaking (PO).

Figure 3.12. Cayley Reef (17-023)

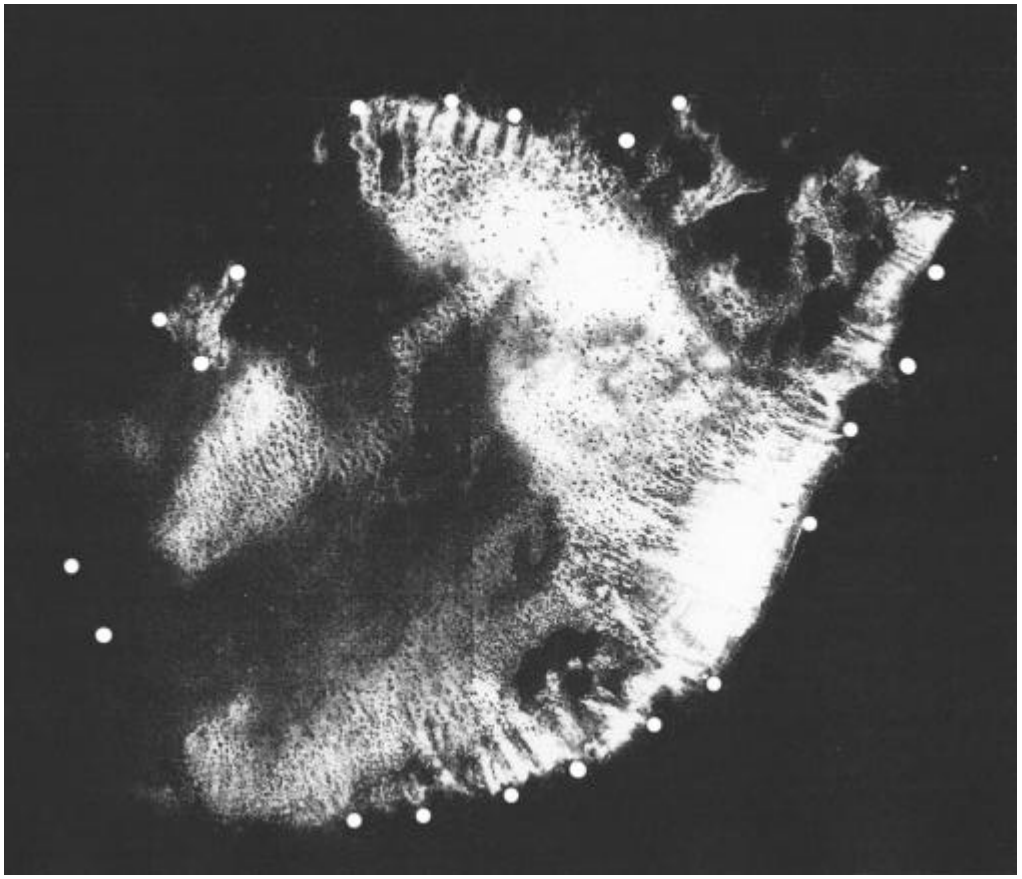


Figure 3.12.1. Aerial photograph of Cayley Reef (17-023). White dots indicate the approximate locations of the 20 sites surveyed in February 2000.

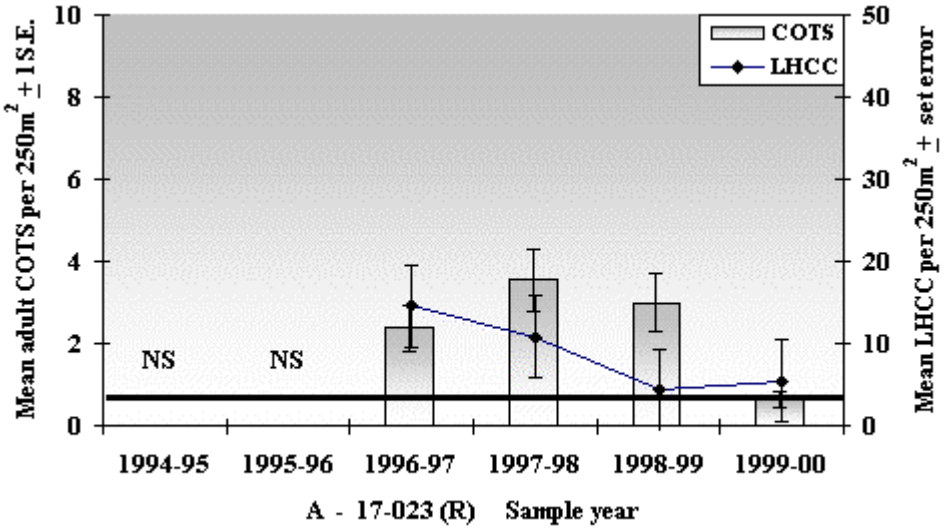
Table 3.12.a. Reef status classification for Reef 17-023 since 1994-95.

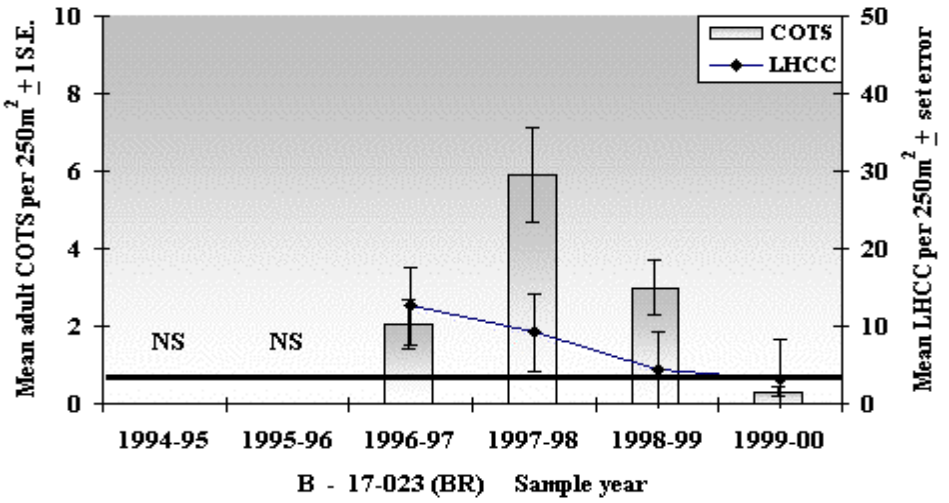
	Reef Status Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef				ASO	ASO	PSO
Front Reef	NS	NS	AO	ISO	NS	ISO
Entire Reef						

Table 3.12.b. Mean densities (±1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1999-00. Values in brackets are total *A. planci* counts.

	Mean Densities (±1SE) (per 250 m^2)		
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**
Back Reef (BR)	1.00±0.34 (20)	0.25±0.10 (5)	0.30±0.13 (6)

Front Reef (FR)	1.90±0.40 (38)	0.65±0.26 (13)	1.00±0.36 (20)
Entire Reef (BR+FR)	1.45±0.27 (58)	0.45±0.14 (18)	0.65±0.19 (26)





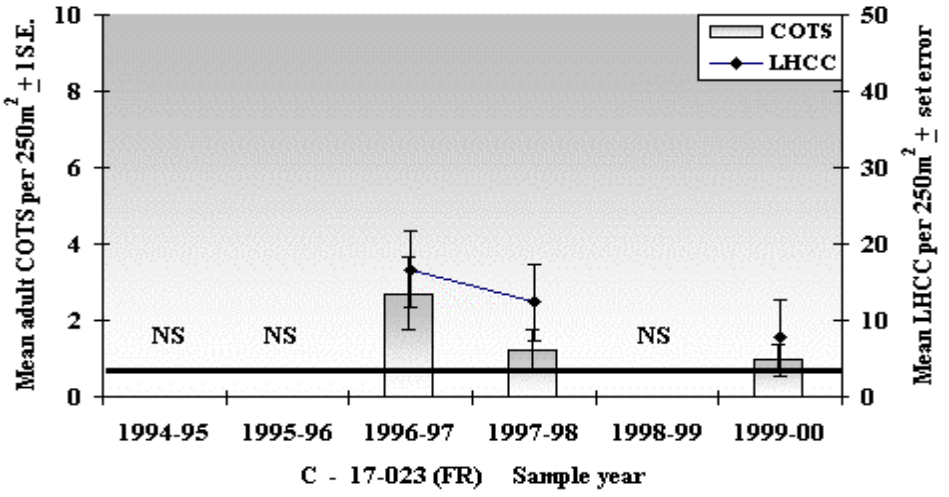


Figure 3.12.2. Reef 17-023. Trends in the mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back-reef zone (B-BR) and in the front-reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbreaking population.

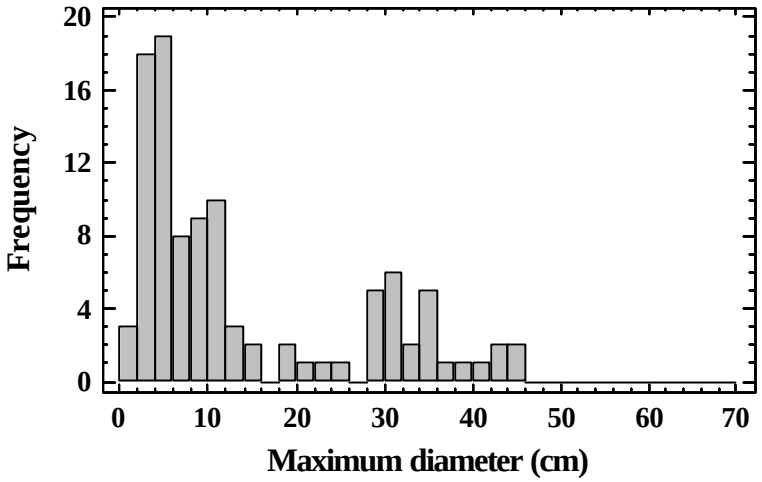


Figure 3.12.3. Size-frequency plot of *A. planci* observed at Reef 17-023 in February 2000.

Summary

When first surveyed in 1996-97, Cayley Reef (17-023) supported an Active reef-wide Outbreak (AO). The Active Spot Outbreak (ASO) in the back-reef zone persisted for three years during which live hard coral cover (LHCC) declined from 10-15% to 0-5% cover. The adult population of *A. planci* had virtually collapsed by 1999-00, probably as a result of the significant reduction in LHCC in recent years.

In contrast, densities of sub-adult and adult starfish in the front-reef zone are again approaching unsustainably high densities. The front-reef zone is now classified as an Incipient Sport Outbreak (ISO) suggesting that the remnant coral cover of 10% may be further reduced in the near future.

Figure 3.13. Feather Reef (17-034)

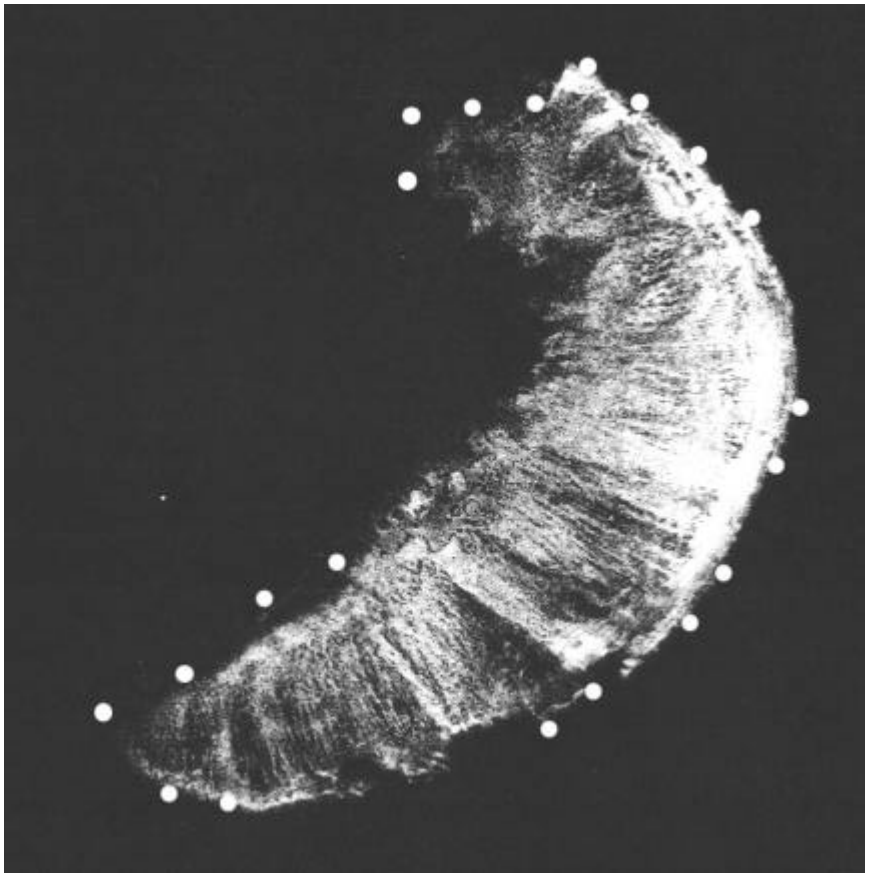


Figure 3.13.1. Aerial photograph of Feather Reef (17-034) White dots indicate the approximate locations of the 20 sites surveyed in March 2000.

Table 3.13.a. Reef status classifications for Reef 17-034 since 1994-95.

	Reef Status Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef				ISO	ASO	ASO
Front Reef				NO	ISO	ASO
Entire Reef	NS	NO	NO			AO

Table 3.13.b. Mean densities (±1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1999-00. Values in brackets are total *A. planci* counts.

	Mean Densities (±1SE) (per 250 m^2)		
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**
Back Reef (BR)	0.65±0.23 (13)	7.00±2.92 (140)	21.20±5.28 (424)

Front Reef (FR)	1.20±0.34 (24)	5.10±1.52 (102)	17.35±4.86 (347)
Entire Reef (BR+FR)	0.93±0.21 (37)	6.05±1.63 (242)	19.28±3.56 (771)

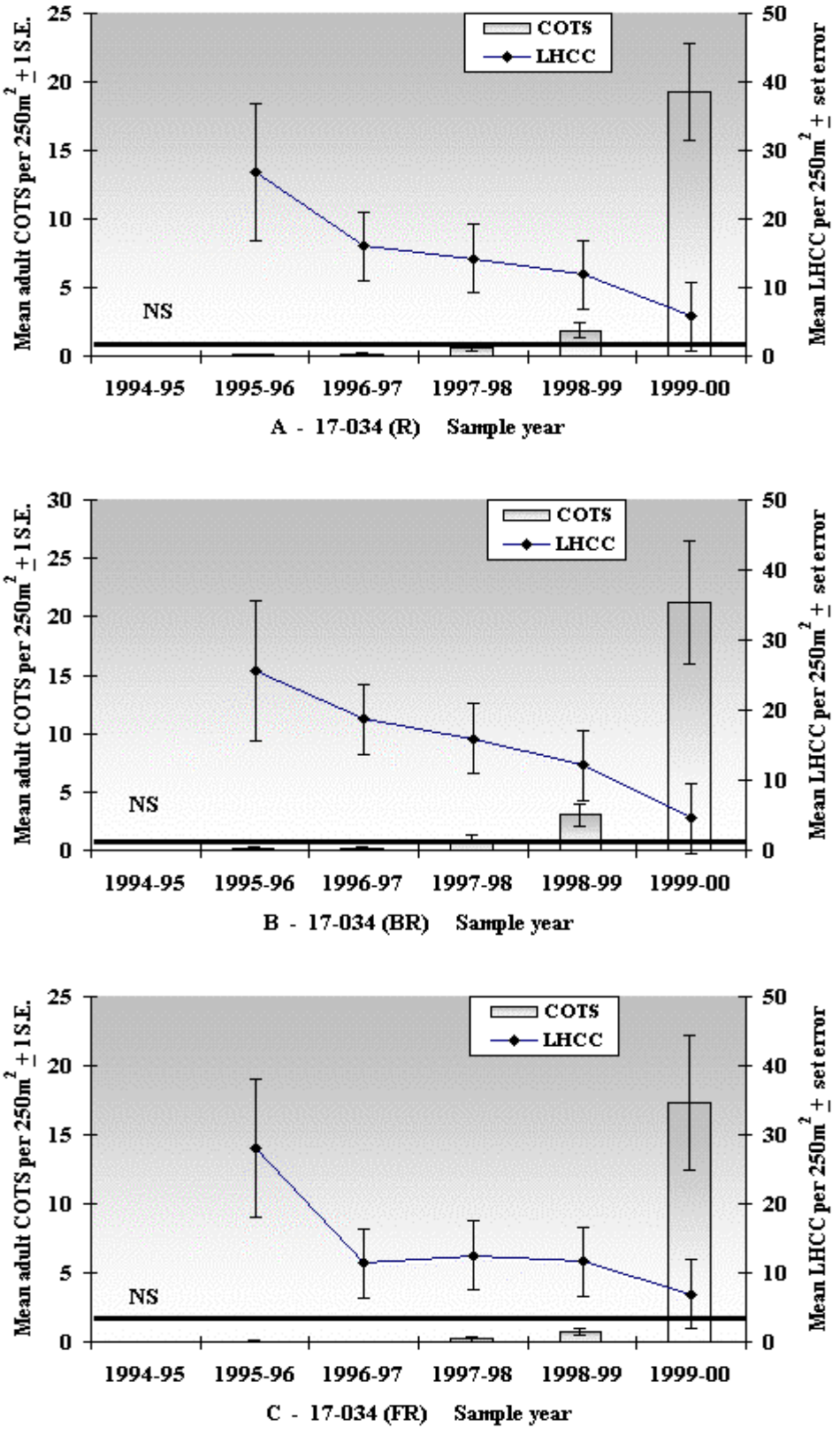


Figure 3.13.2. Reef 17-034. The mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back-reef zone (B-BR) and in the front-reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbreaking population.

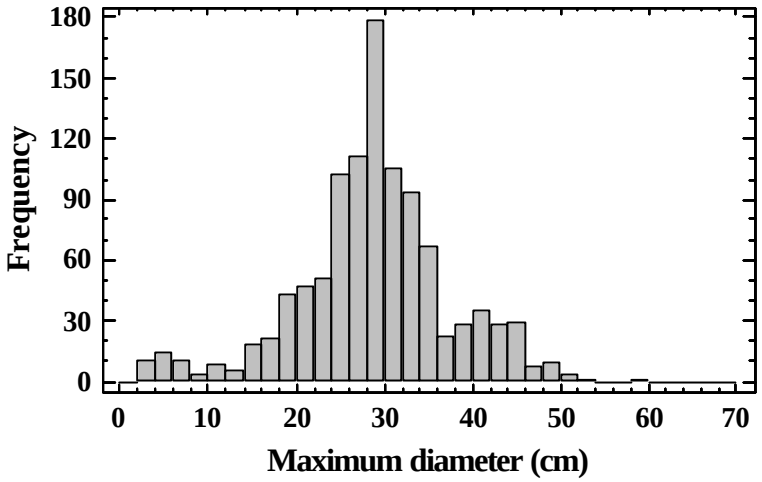


Figure 3.13.3. Size-frequency plot of *A. planci* observed at Reef 17-034 in March 2000.

Summary

The first signs of unsustainable densities of *A. planci* developing on Feather Reef (17-034) were recorded in 1997-98 when surveys detected an Incipient Spot Outbreak (ISO) in the back-reef zone. As predicted, an Active Spot Outbreak (ASO) had developed in this zone within 12 months after the survey. The 1998-99 surveys also detected unsustainably high densities of juvenile and sub-adult starfish in both reef zones, suggesting the density of adult starfish across the reef were likely to increase. Furthermore, the 1998-99 surveys suggested that both starfish densities and live hard coral cover (LHCC) would rapidly change as a result of the large numbers of juvenile and sub-adult starfish approaching maturity.

These predictions have been confirmed and actively outbreaking densities of adult COTS were observed in both reef zones during the 1999-00 surveys. Adult densities exceed sustainable levels by a factor of about 29 in the back-reef zone and about 25 in the front-reef zone. As a direct consequence of COTS feeding activity, LHCC has been reduced to an average of 5% compared with 25-30% mean LHCC recorded in 1995-96. Given the extremely high densities of current COTS populations in both the back- and front-reef zones, a further decline LHCC, across the reef is likely to occur within 6 to 12 months.

Figure 3.14. Eddy Reef (17-047)

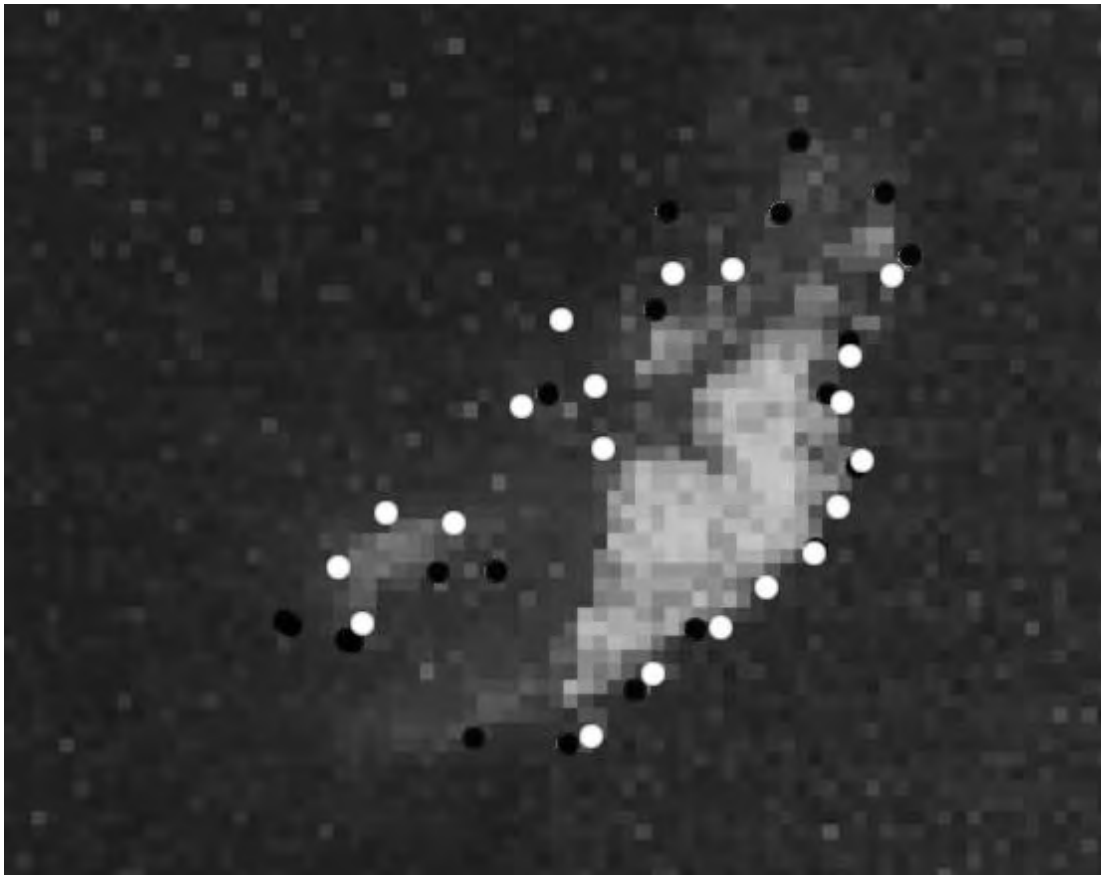


Figure 3.14.1. Aerial photograph of Eddy Reef (17-047). White dots indicate the approximate locations of the 20 sites surveyed in March 2000.

Table 3.14.a. Reef status classifications for Reef 17-047 since 1994-95.

	Reef Status Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef			NO		AO	ASO
Front Reef	NS	NS	NS	NS		ASO
Entire Reef						AO

Table 3.14.b. Mean densities (±1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1999-00. Values in brackets are total *A. planci* counts.

	Mean Densities (±1SE) (per 250 m^2)		
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**

Back Reef (BR)	0.50±0.21 (10)	6.95±2.50 (139)	6.95±1.94 (139)
Front Reef (FR)	0.50±0.14 (10)	1.50±0.32 (30)	1.40±0.34 (28)
Entire Reef (BR+FR)	0.50±0.12 (20)	4.23±1.32 (169)	4.18±1.07 (167)

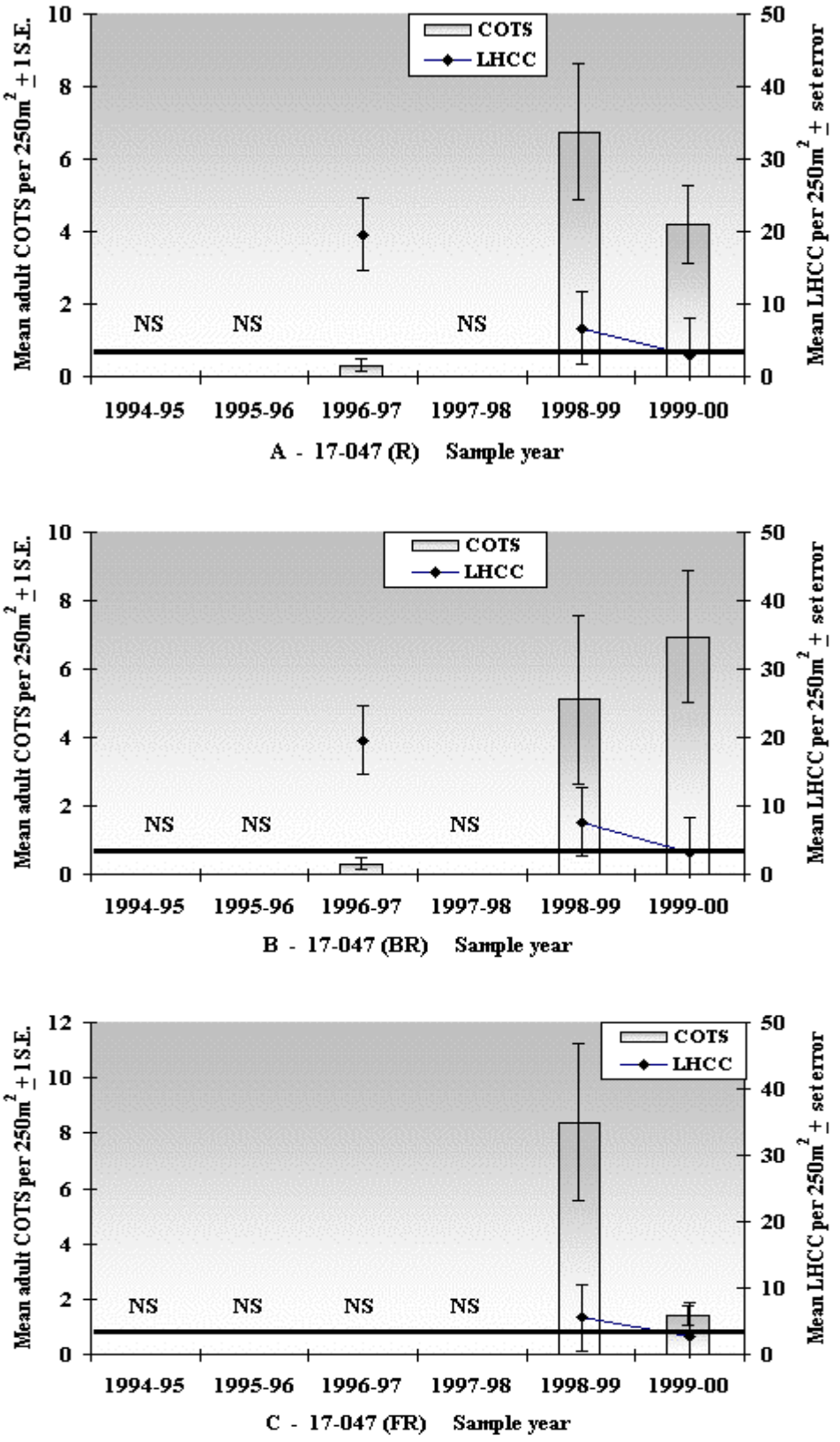


Figure 3.14.2. Reef 17-047. The mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back-reef zone (B-BR) and in the front-reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbreaking population.

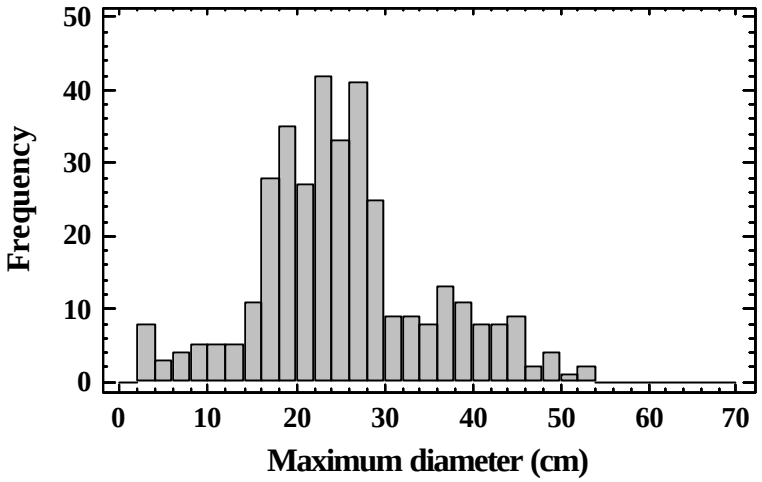


Figure 3.14.3. Size-frequency plot of *A. planci* observed at Reef 17-047 in March 2000.

Summary

In 1998-99, Eddy Reef (17-047) supported an Active reef-wide Outbreak (AO) with densities of adult *A. planci* in the front-reef zone at more than 10-times sustainable levels. The reef-wide outbreak has continued in 1999-00 with adult densities in both reef zones remaining at unsustainable levels. The population of adult COTS in the back-reef area has remained very high (at about 10-times sustainable levels). The number of adult starfish in the front-reef zone has collapsed to slightly above outbreaking densities. Live hard coral cover (LHCC) across the reef has been reduced significantly to an average of less than 5% due to COTS feeding activity.

Figure 3.15. Beaver Reef (17-051)

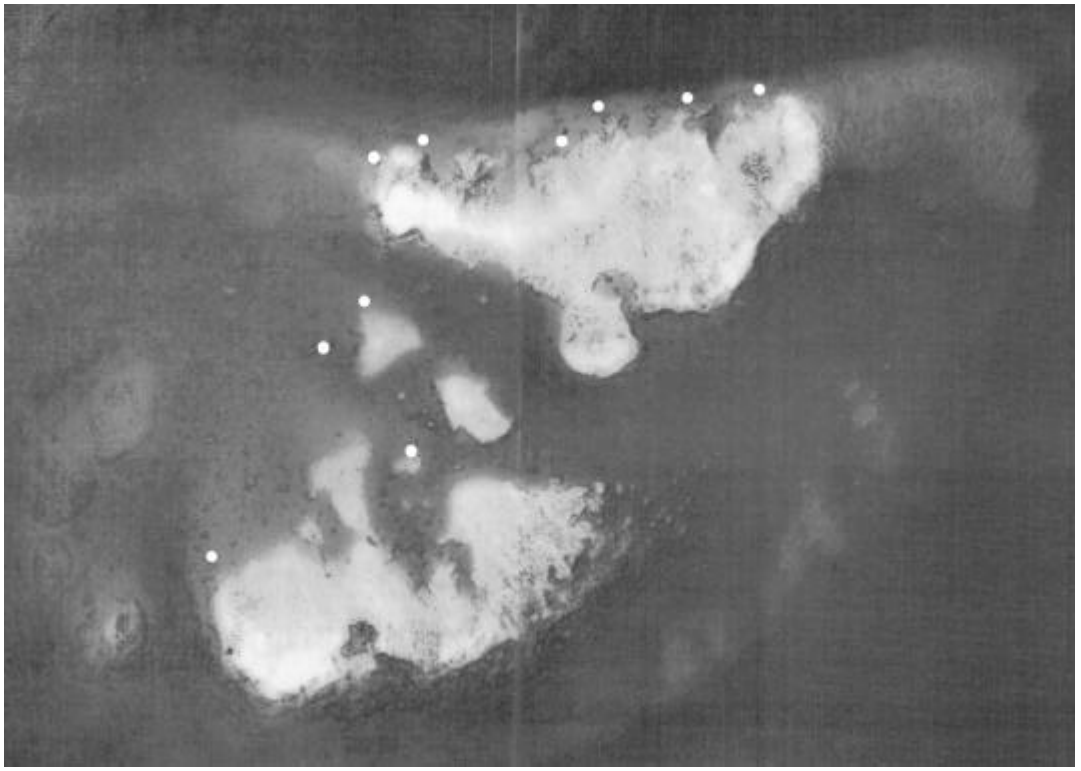


Figure 3.15.1. Aerial photograph of Beaver Reef (17-051). White dots indicate the approximate location of 10 sites surveyed in March 2000.

Table 3.15.a. Summary of reef status classifications for Reef 17-051 since 1994-95.

	Reef Status Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef	NS	NS	NS	NS	NS	ASO
Front Reef	NS	NS	NS	NS	NS	NS
Entire Reef	NS	NS	NS	NS	NS	

Table 3.15.b. Mean densities (±1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1999-00. Values in brackets are total *A. planci* counts.

Mean Densities (±1SE) (per 250 m^2)			
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**
Back Reef (BR)	1.50±0.80 (30)	7.15±1.78 (143)	3.80±0.84 (76)
Front Reef (FR)	NS	NS	NS

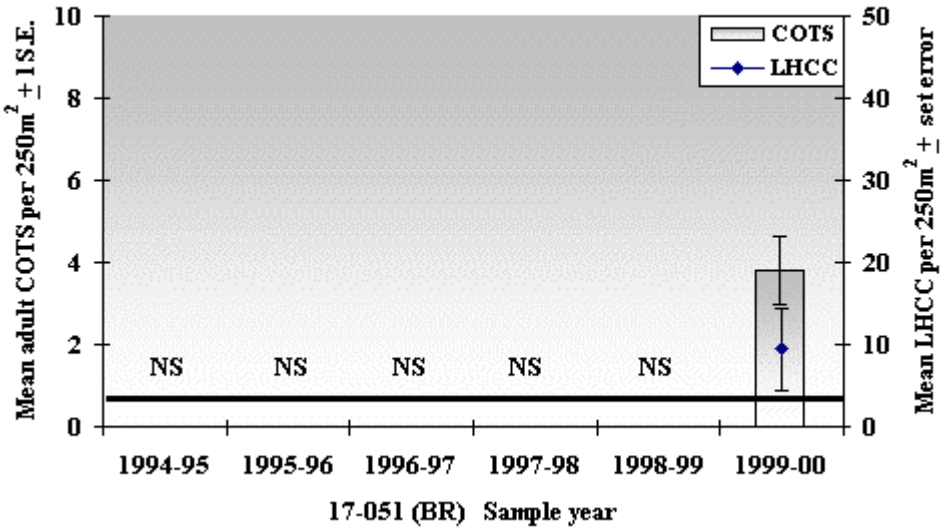


Figure 3.15.2. Reef 17-051. The mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) in the back-reef zone (BR) observed in March 2000. The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbreaking population.

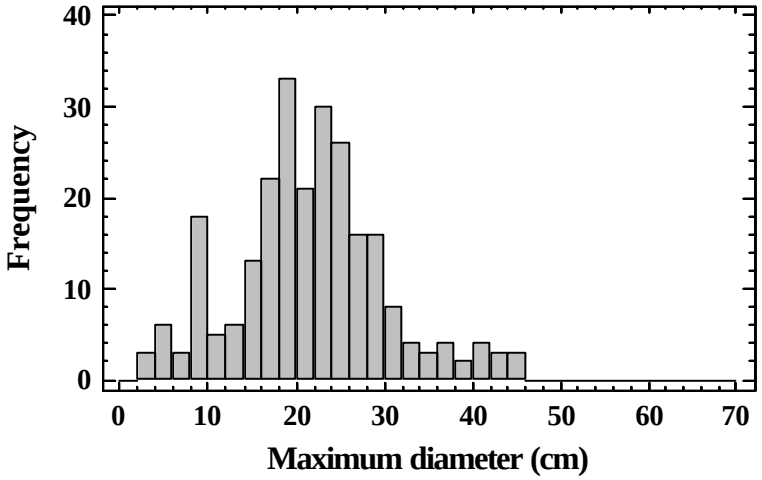


Figure 3.15.3. Size-frequency plot of *A. planci* observed at Reef 17-051 in March 2000.

Summary

The back-reef zone of Beaver Reef (17-051) was surveyed in 1999-00 as a substitute for the front-reef zone at Taylor Reef (17-064) which was inaccessible because of persistent and severe weather conditions during the surveys.

The back-reef zone supports an Active Spot Outbreak (ASO) with current adult densities approximately five-times above sustainable levels. The outbreak is likely to continue for some time and adult starfish densities increase further as significant numbers of sub-adult starfish approach maturity.

Live hard coral cover (LHCC) in the back-reef area was recorded at an average of around 10% in 1999-00.

Figure 3.16. Taylor Reef (17-064)

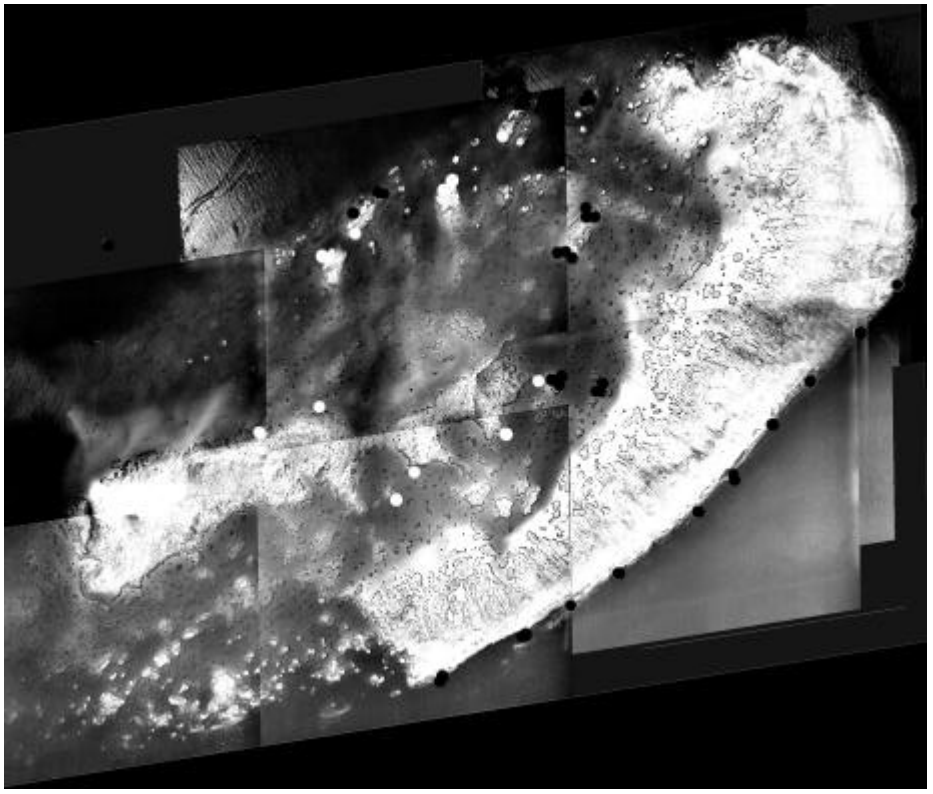


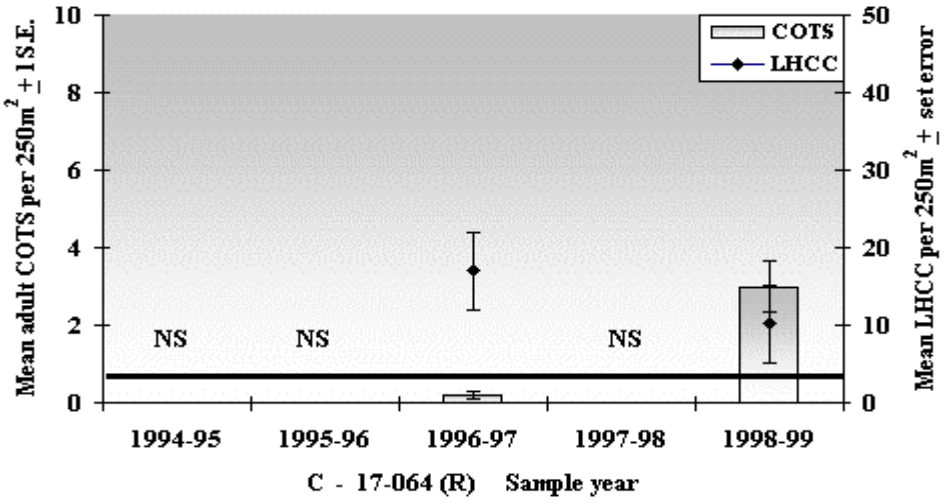
Figure 3.16.1. Aerial photograph of Taylor Reef (17-064). White dots indicate the approximate location of 10 sites surveyed in March 2000.

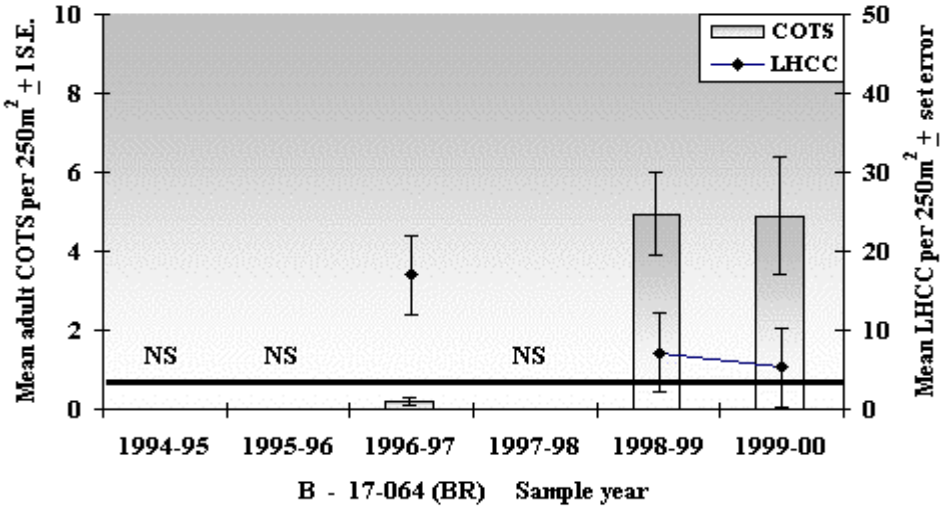
Table 3.16.a. Summary of reef status classifications for Reef 17-064 since 1994-95.

	Reef Status Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef	NS	NS	NO	NS	ASO	ASO
Front Reef			NS		ISO	NS
Entire Reef						

Table 3.16.b. Mean densities (±1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1998-99. Values in brackets are total *A. planci* counts.

	Mean Densities (±1SE) (per 250 m^2)		
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**
Back Reef (BR)	1.20±0.39 (24)	2.50±0.73 (50)	4.98±1.50 (98)
Front Reef (FR)	NS	NS	NS
Entire Reef (BR + FR)			





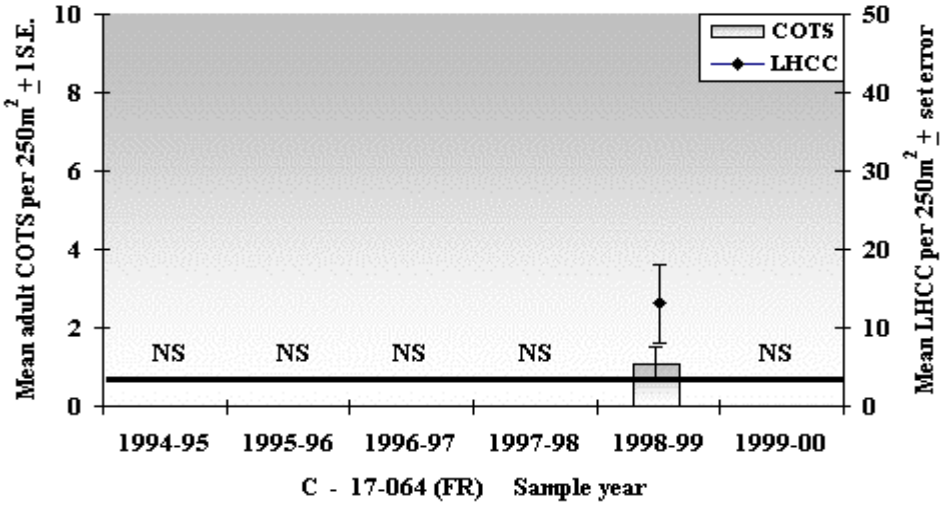


Figure 3.16.2. Reef 17-064. The mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back-reef

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.

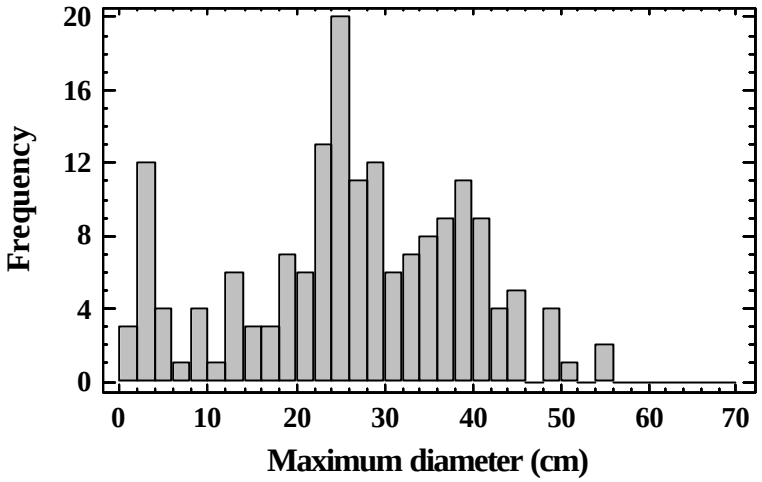


Figure 3.16.3. Size-frequency plot of *A. planci* observed at Reef 17-064 in March 2000.

Summary

The Active Spot Outbreak (ASO) recorded in the back-reef zone at Taylor Reef in 1998-99 has continued into 1999-00 with numbers of adult *A. planci* remaining at six times above sustainable densities.

As a consequence of starfish feeding activity, live hard coral cover (LHCC) in the back-reef zone has declined to about 5%. This compares with 15-20% LHCC recorded in this reef zone in 1996-97.

Persistent, severe weather conditions prevented a survey of the exposed front-reef zone where an Incipient Spot Outbreak (ISO) was detected in 1998-99.

Figure 3.17. Kelso Reef (18-030)

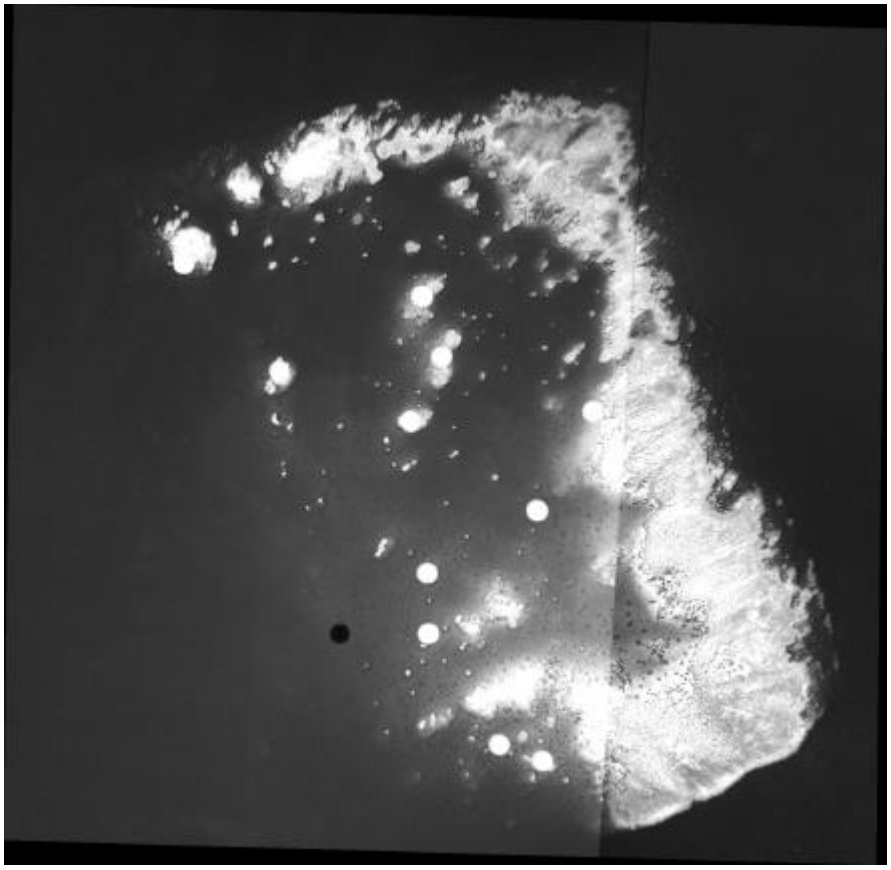


Figure 3.17.1. Aerial photograph of Kelso Reef (18-030). White dots indicate the approximate locations of the 10 sites surveyed in April 2000.

Table 3.17.a. Summary of reef status classifications for Reef 18-030 since 1994-95.

	Reef Status Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef	NS	NS	NS	ISO	NS	ASO
Front Reef				NO		NS
Entire Reef						

Table 3.17.b. Mean densities (±1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1999-00. Values in brackets are total *A. planci* counts.

	Mean Densities (±1SE) (per 250 m^2)		
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**
Back Reef (BR)	0.90±0.38 (18)	1.50±0.37 (30)	3.75±0.80 (75)

Front Reef (FR)	NS	NS	NS
Entire Reef (BR + FR)			

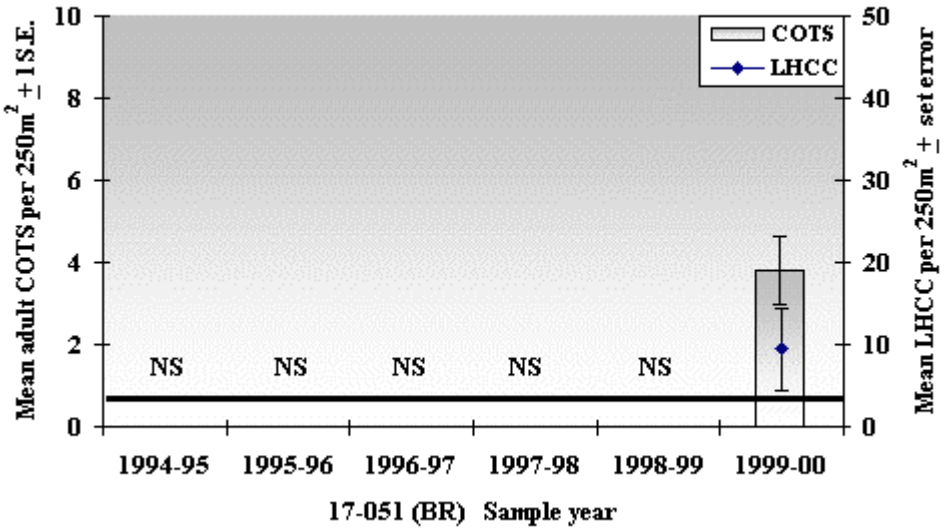


Figure 3.17.2. Reef 18-030. The mean number of adult COTS (estimated age three years or older) and mean live hard coral cover (LHCC) in the back-reef zone (BR) as observed in April 2000. The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbreaking population.

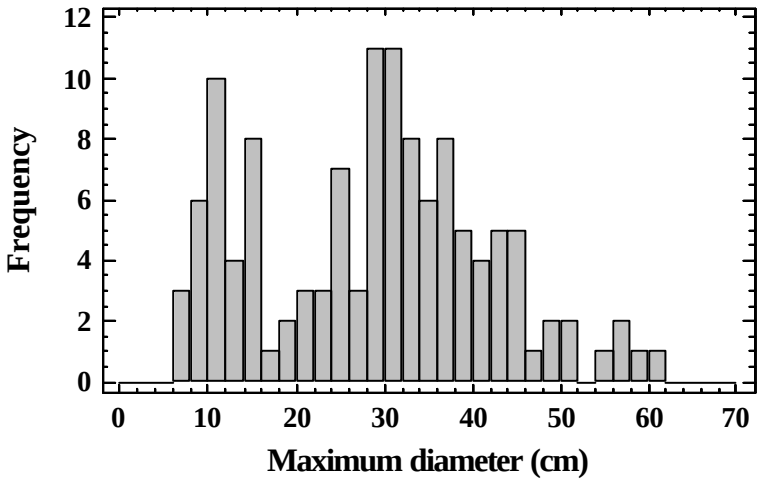


Figure 3.17.3. Size-frequency of *A. planci* observed at Reef 18-030 in April 2000.

Summary

Kelso Reef was first surveyed in 1997-98 when we detected an Incipient Spot Outbreak (ISO) in the back-reef zone. Anecdotal information provided by a local reef tourism venture, Pure Pleasure Cruises, confirmed that an active outbreak of adult starfish developed within 12 months of our initial survey. In 1999-00, Kelso Reef was surveyed as a substitute reef for Lodestone Reef (18-078) which remained inaccessible for the duration of the survey in April 2000.

The 1999-00 survey of Kelso Reef found the outbreak was ongoing with adult densities of COTS remaining at approximately five-times sustainable levels. In the two years since the previous survey, live hard coral cover (LHCC) in the back-reef zone has been reduced from 20% to about 15%.

Persistent severe weather conditions prevented the survey of the exposed front-reef zone.

Figure 3.18. Little Kelso Reef (18-031)

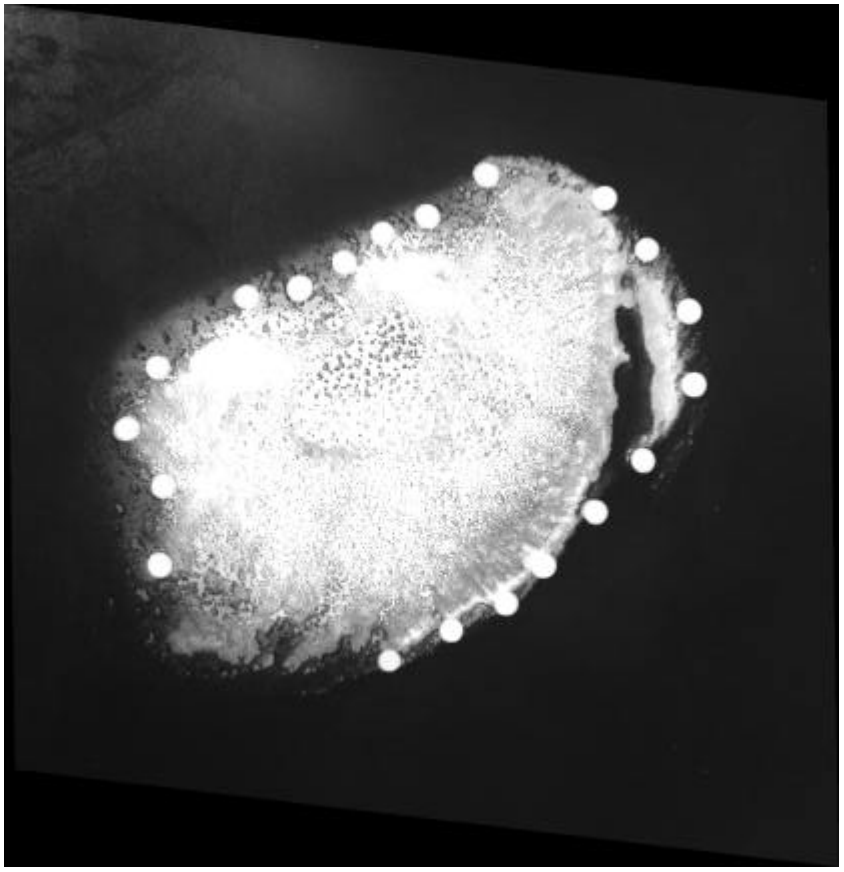


Figure 3.18.1. Aerial photograph of Little Kelso Reef (18-031). White dots indicate the approximate locations of 20 sites surveyed in April 2000.

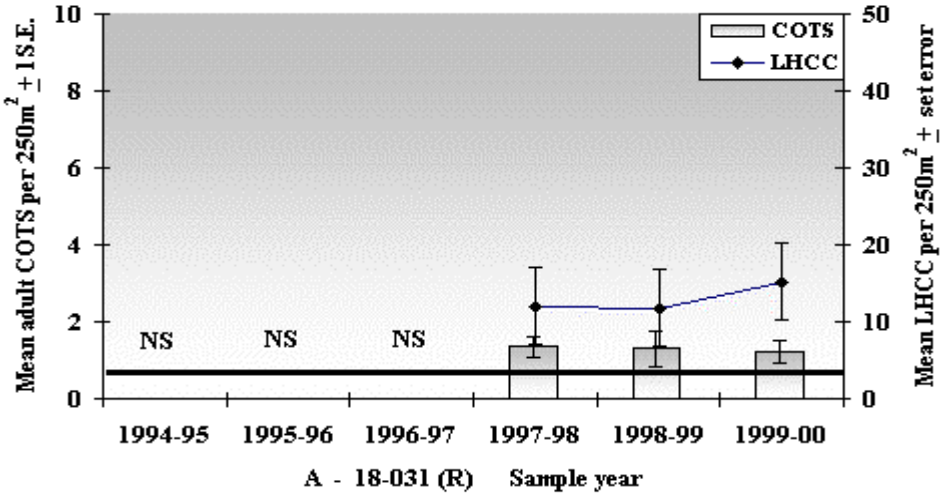
Table 3.18.a. Reef status classifications for Reef 18-031 since 1994-95.

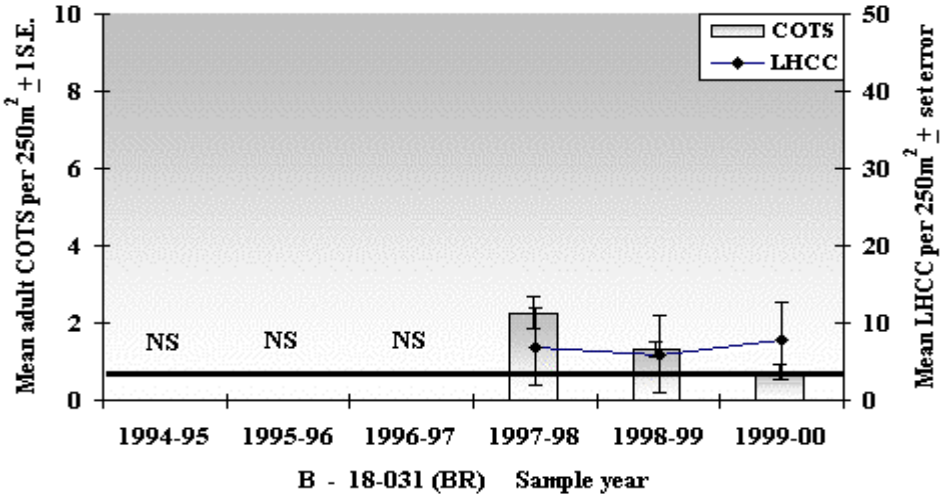
	Reef Status Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef	NS	NS	NS	ASO	ASO	ISO
Front Reef				NO	NO	ASO
Entire Reef						

Table 3.18.b. Mean densities (±1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1999-00. Values in brackets are total *A. planci* counts.

	Mean Densities (±1SE) (per 250 m^2)		
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**
Back Reef (BR)	0.00±0.00 (0)	0.35±0.17 (7)	0.75±0.20 (15)

Front Reef (FR)	2.35±0.87 (47)	0.80±0.20 (16)	1.70±0.50 (34)
Entire Reef (BR+FR)	1.18±0.47 (47)	0.58±0.13 (23)	1.23±0.28 (49)





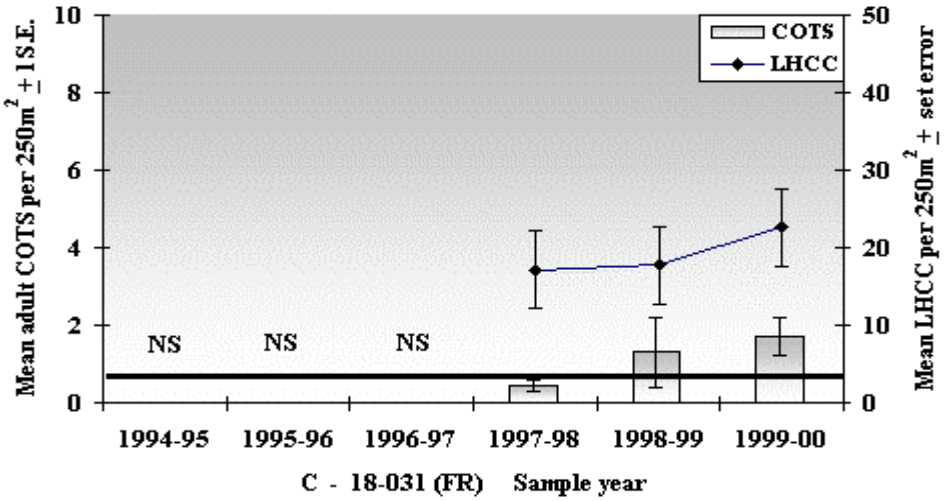


Figure 3.18.2. Reef 18-031. The mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back-reef zone (B-BR) and in the front-reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbreaking population.

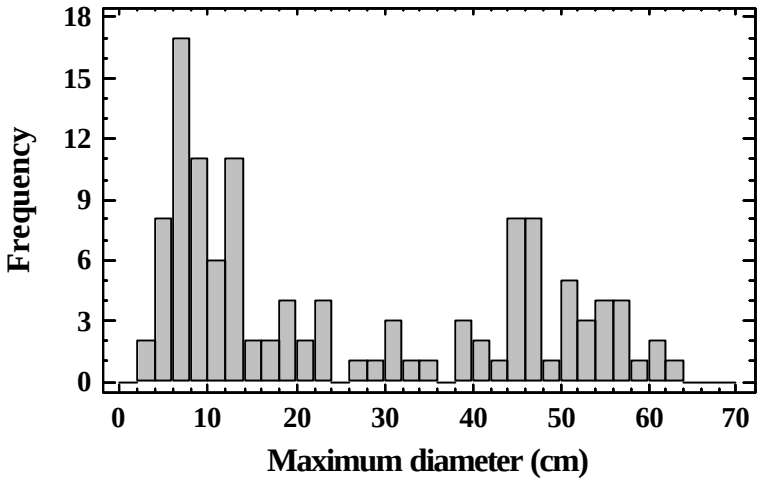


Figure 3.18.3. Size-frequency plot of *A. planci* observed at Reef 18-031 in April 2000.

Summary

Little Kelso Reef (18-031) was first surveyed in 1997-98 when an Active Spot Outbreak (ASO) was recorded in the back-reef zone. The density of adult *A. planci* has declined marginally since the initial survey, however, the adult COTS population in the back-reef zone remains near the upper limit of a sustainable population. Live hard coral cover (LHCC) has also remained stable at 5-10%.

The adult starfish population in the front-reef zone continues to increase and supports an ASO. The significant densities of both juvenile and sub-adult *A. planci* observed in this zone in 1999-00 suggest that the starfish density will further increase in the near future. The average LHCC of 20-25% is likely to be significantly affected by the numbers of adult COTS in this zone.

Figure 3.19. John Brewer Reef (18-075)

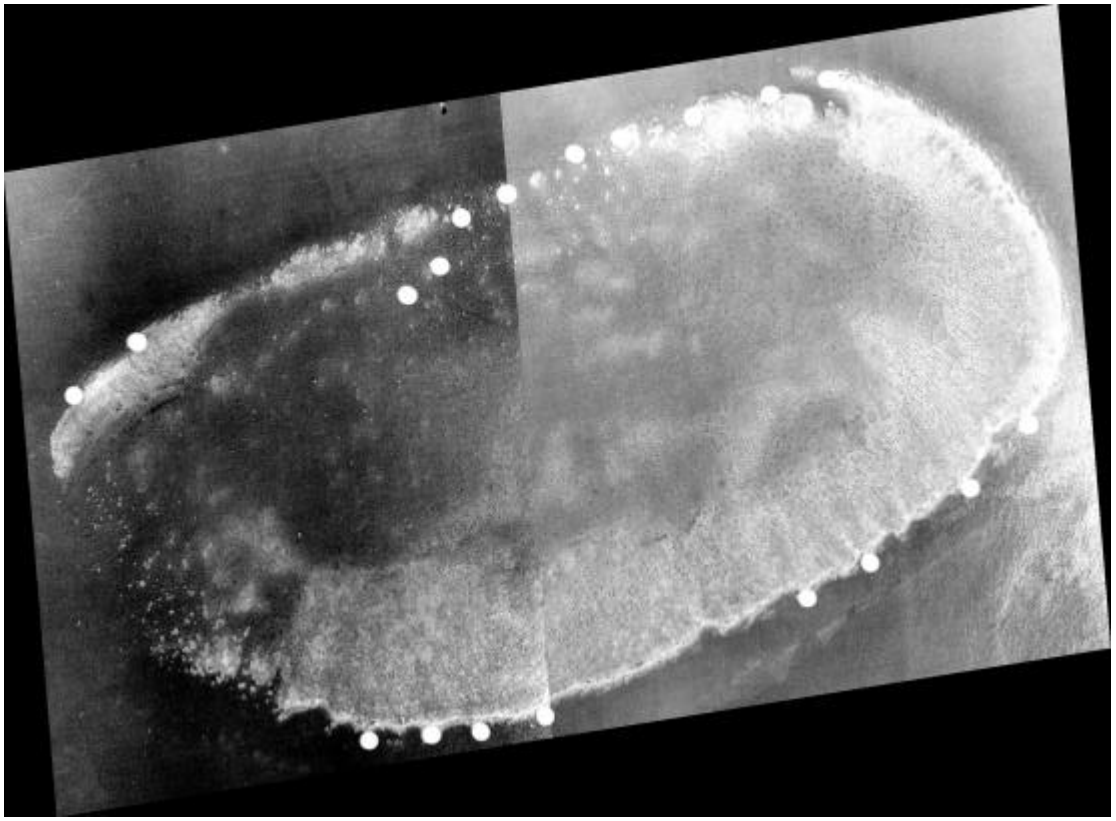


Figure 3.19.1. Aerial photograph of John Brewer Reef (18-075). White dots indicate the approximate locations of the 20 sites surveyed in April 2000.

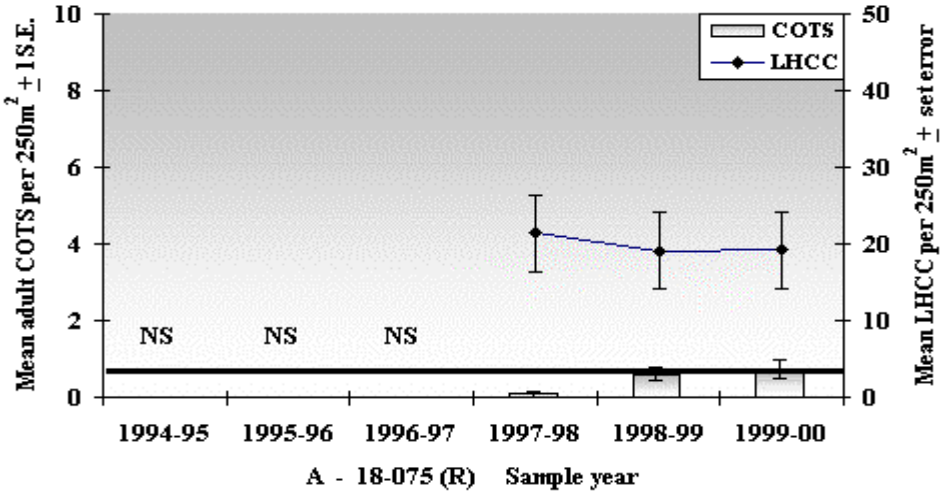
Table 3.19.a. Reef status classifications for Reef 18-075 since 1994-95.

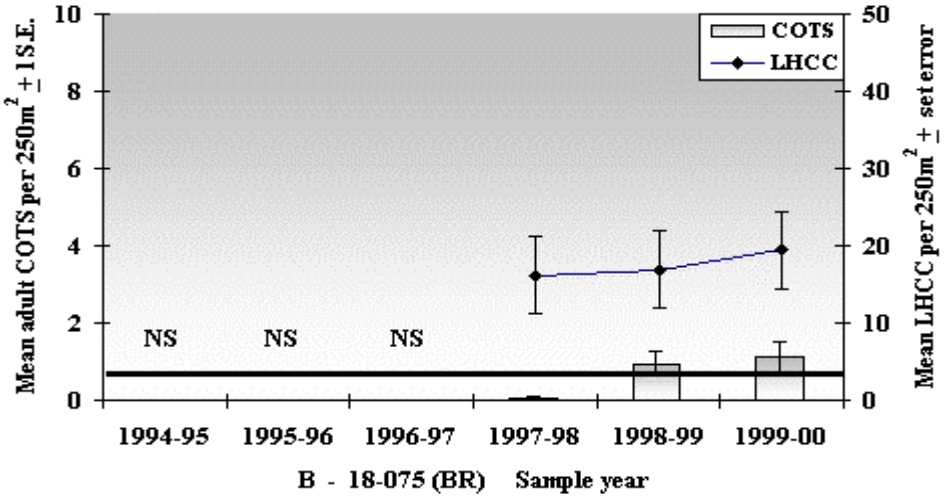
	Reef Status Classification					
Sample Area	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
Back Reef	NS	NS	NS	NO	NO	ISO
Front Reef	NS	NS	NS			ISO
Entire Reef						IO

Table 3.19.b. Mean densities (±1 SE) per 250 m^2 of estimated age classes of *A. planci* across reef zones in 1999-00. Values in brackets are total *A. planci* counts.

	Mean Densities (±1SE) (per 250 m^2)		
SAMPLE AREA	**Juveniles (est. age 1)**	**Sub-adults (est. 2 years)**	**Adults (est. age 3 or older)**
Back Reef (BR)	0.55±0.22 (11)	0.85±0.35 (17)	1.10±0.40 (22)

Front Reef (FR)	4.45±0.85 (89)	2.45±0.69 (49)	0.35±0.18 (7)
Entire Reef (BR+FR)	2.50±0.53 (100)	1.65±0.40 (66)	0.73±0.23 (29)





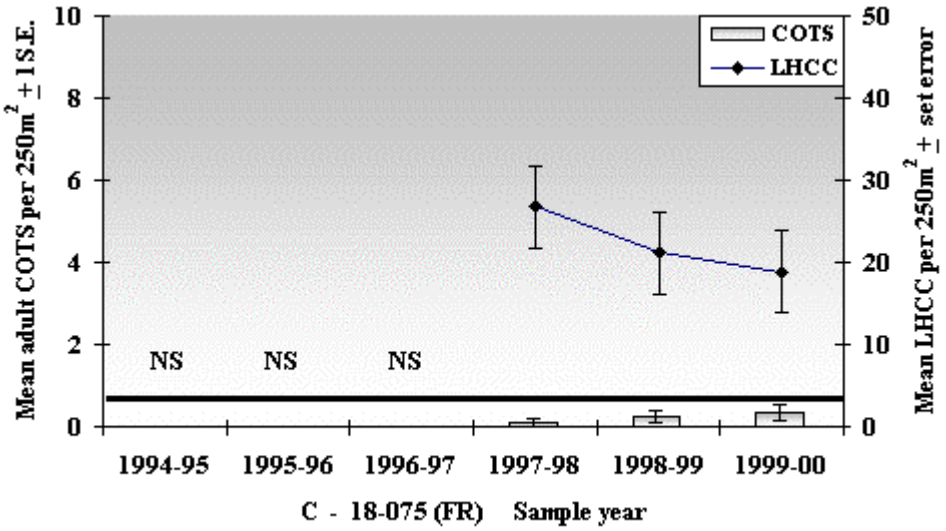


Figure 3.19.2. Reef 18-075. The mean number of adult COTS (estimated age of 3 years or older) and mean live hard coral cover (LHCC) across the entire reef (A-R), in the back-reef zone (B-BR) and in the front-reef zone (C-FR). The line at 0.75 adult COTS per 250 m^2 indicates the upper limit of a sustainable, non-outbreaking population.

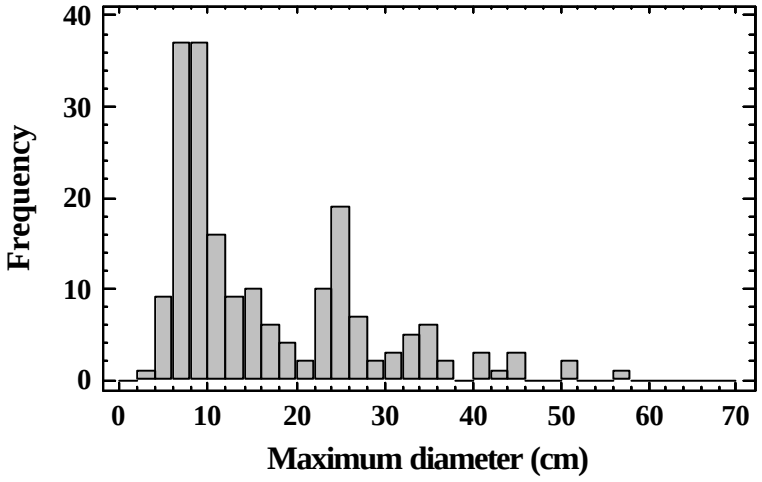


Figure 3.19.3. Size-frequency plot of *A. planci* observed at Reef 18-075 in April 2000.

Summary

John Brewer Reef (18-075) was first surveyed in 1997-98 when relatively little starfish activity was evident. However, since this initial survey, densities of *A. planci* of all three age categories have slowly increased in both the back- and front-reef zone. The combined densities of sub-adult and adult COTS observed in both reef zones in 1999-00 warrant the

classification of Incipient reef-wide Outbreak (IO), ie. outbreaking densities of adult starfish are likely to develop within six to 12 months.

Currently, live hard coral cover (LHCC) across the reef has remained relatively stable at an average of around 20%. However, unsustainably high densities of juvenile *A. planci* in the front-reef zone and to a lesser degree in the back-reef zone suggest a strong potential for further increases in starfish density within 12-18 months. The current average LHCC (20%) is sufficient for this cohort of 1998-99 recruits to grow and reach maturity.

3.3 Differences in the abundance of *A. planci* across three spatial scales

3.3.1 Regional-scale (latitudinal) differences in the abundance of *A. planci*

We detected significant regional-scale differences in the median abundance of two of the three estimated age classes of *A. planci* (Table 4).

Median notches on the relevant Box-and-Whisker plots (Figure 4) identify the following statistical relationships in the abundance of the three estimated age classes of *A. planci* across the selected latitudinal bands:

For juvenile COTS: LAT_BAND 1 = LAT_BAND 2 = LAT_BAND 3
For sub-adult COTS: LAT_BAND 3 > LAT_BAND 1 > LAT_BAND 2
For adult COTS: LAT_BAND 3 > LAT_BAND 2 > LAT_BAND 1

Table 4. Summary of Kruskal-Wallis statistics resulting from tests for significant differences in the median densities of estimated age classes of *A. planci* between the three latitudinal bands sampled in 1999-00. * indicate statistically significant differences. A subset of data was analysed to ensure a balanced sampling design. The following reef zones were excluded from this analysis (see also Table 1): 15-024(FR), 15-095(FR), 16-024(FR), 17-004(FR) and 17-051(BR).

Latitudinal band (LAT_BAND)	**Sample size (transects)**	**Average rank Juveniles (est. age 1)**	**Average rank Sub-adults (est. age 2)**	**Average rank Adults (est. age 3 or older)**
1 (14°31' - 16°00'S)	200	292.59	295.04	234.01
2 (16°01' - 17°30'S)	200	318.02	275.72	255.95
3 (17°31' - 19°00'S)	200	290.89	330.74	411.53
Test statistic	**-**	**3.66**	**11.89**	**176.33**
P - value	**-**	**0.16**	**0.002 ***	**0.0 ***

Juvenile starfish (est. age 1). There were no significant differences in the abundance of juvenile *A. planci* between the three latitudinal bands.

Sub-adult starfish (est. age 2) were significantly more abundant on reefs within latitudinal band 3 (from offshore Mission Beach to Townsville) than the other two bands. There was a density gradient for sub-adult starfish in latitudinal bands 1 and 2. The northern region which includes the Daintree coast and the area offshore Cooktown (latitudinal band 1) recorded a higher median density of sub-adult *A. planci* than the central region off shore Cairns and Port Douglas (latitudinal band 2).

Adult starfish (est. age 3 or older) were significantly more abundant on reefs located within latitudinal band 3 (offshore from Mission Beach to Townsville) than within the other two bands. There was a significant density gradient for adult starfish in latitudinal bands 1 and 2, with the northern region (from offshore Cooktown to the Daintree coast) recording the lowest densities of adult *A. planci.*

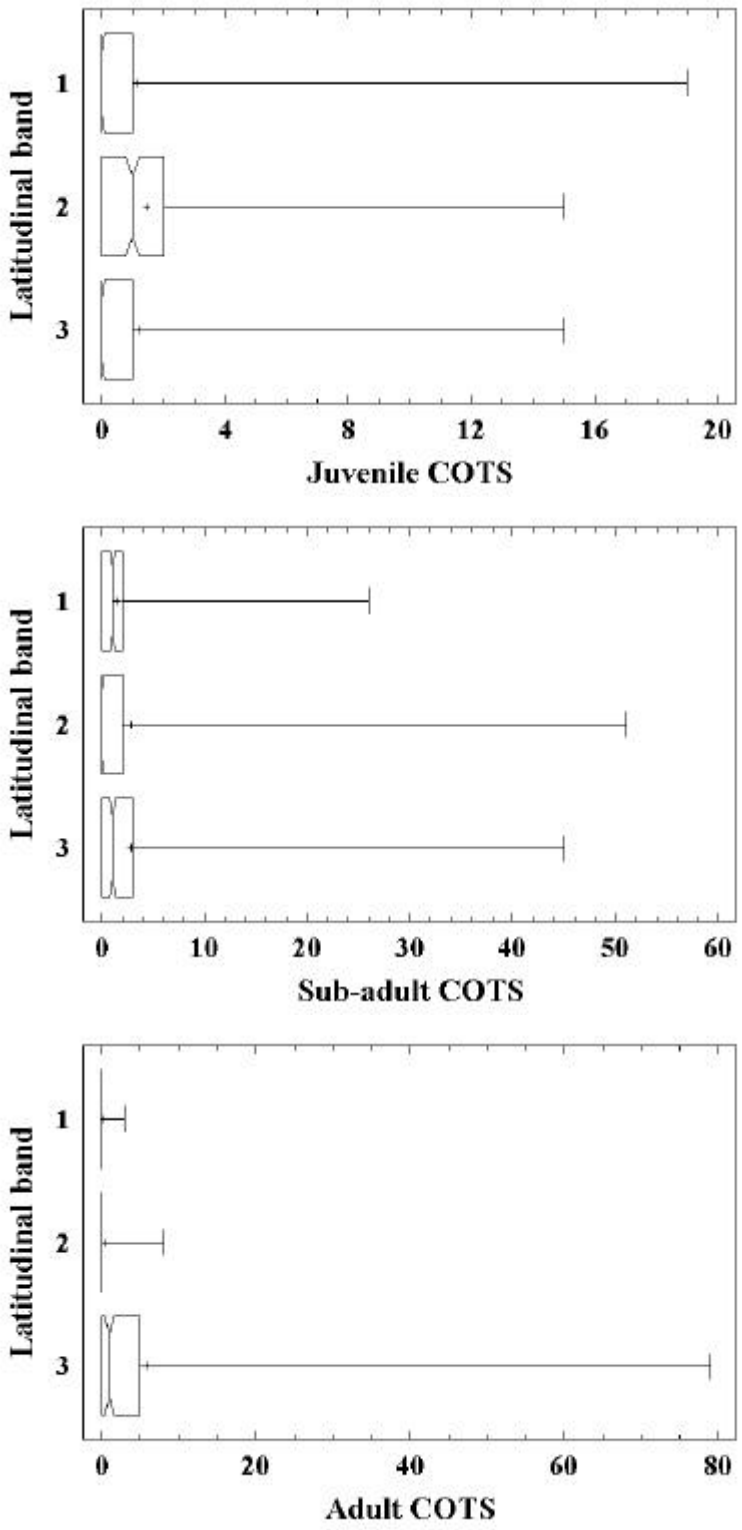


Figure 4. Box-and-Whisker plots showing density distributions of estimated age classes of *A. planci* across the three latitudinal bands surveyed in 1999-00. Notches were used to assess the significance of differences between median densities (Kruskal-Wallis tests). (+) indicates the mean density for the respective age classes.

3.3.2 Reef-scale differences in the abundance of *A. planci*

There were significant differences in the median abundance of *A. planci* between reefs for all three age classes. Statistical differences were highly significant with P values from 0.0 to <0.0001 (Table 5). Median notches in Figure 5 identify sampling units (reefs) which differ from others.

Table 5. Summary of Kruskal-Wallis statistics testing for significant differences between the median densities of three estimated age classes of *A. planci* on reefs sampled in 1999-00. *indicate statistically significant differences. Data for the following reef zones were excluded to ensure a fully balanced design: 17-051(BR), 17-064(BR) and 18-030(BR).

Reef ID number	Sample size (transects)	Average rank Juveniles (est. age 1)	Average rank Sub-adults (est. age 2)	Average rank Adults (est. age 3 or older)
14-132b	40	297.65	302.14	235.00
15-019	40	320.23	374.20	289.14
15-024	40	349.68	343.46	241.84
15-070	40	287.49	318.48	319.65
15-084	40	338.14	342.75	255.51
15-095	40	290.14	274.43	263.65
16-023	40	445.04	389.85	290.88
16-024	40	265.61	182.63	235.00
16-068	40	318.44	532.66	380.66
17-004	40	348.10	246.39	256.81
17-011	40	312.71	168.08	235.00
17-023	40	353.84	235.79	345.16
17-034	40	302.49	458.24	570.05
17-047	40	256.50	380.13	475.50
18-031	40	261.01	265.29	398.10
18-075	40	380.95	313.51	336.05
Test statistic	**-**	**48.44**	**185.51**	**267.62**
P -value	**-**	**<0.0001 ***	**0.0 ***	**0.0 ***

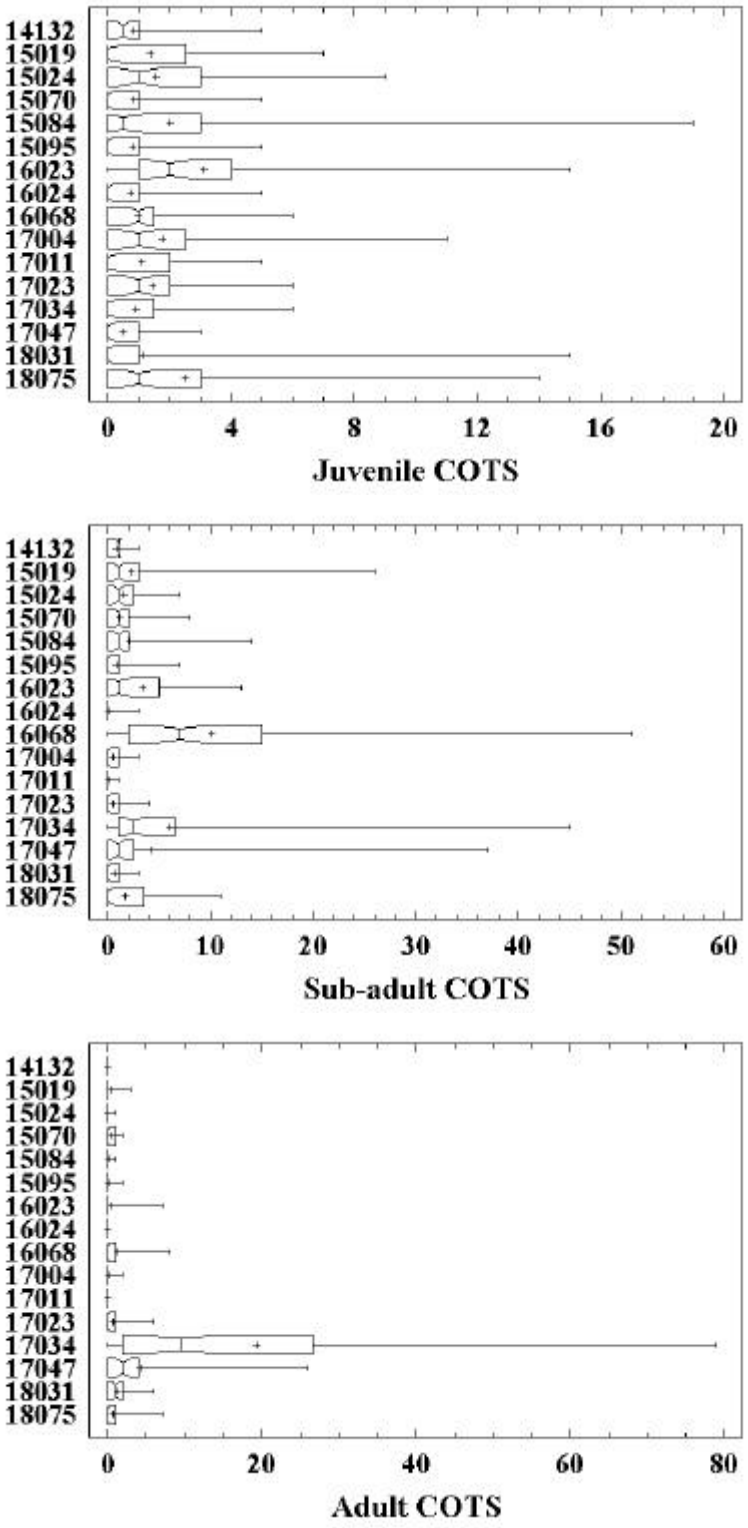


Figure 5. Box-and-Whisker plots showing density distributions of estimated age classes of *A. planci* across reefs surveyed in 1999-00. Notches were used to assess the significance of differences between median densities (Kruskal-Wallis tests). (+) indicates the mean density for the respective age classes at the reef scale.

3.3.3 Within-reef-scale (zonal) differences in the abundance of *A. planci*

Kruskal-Wallis analyses detected significant differences in the median abundance of two of the three estimated age classes of *A. planci* between reef zones. There were significantly higher densities of juvenile starfish in the exposed front-reef zone (FR) than on the protected back-reef zone (BR) (P = 0.0). There were also significantly more sub-adult starfish in the exposed front-reef zone (FR) than the back-reef zone (BR) (P = <0.000001). The analysis did not detect differences in the abundance of adult starfish across the two reef zones (P = 0.26) (Table 6, Figure 6). Only those reefs where both the back- and front-reef zones could be sampled in 1999-00 were included in the analysis. Back-reef zones on reefs 17-051, 17-064 and 18-030 were excluded from the full analysis.

Table 6. Summary of Kruskal-Wallis statistics testing for differences between the median densities of three estimated age classes of *A. planci* across within-reef zones sampled in 1999-00. * indicates significant differences.

		MEDIAN DENSITY		
Within-reef scale (zonal)	**Sample size (transects)**	**Average rank Juveniles (est. age 1)**	**Average rank Sub-adults (est. age 2)**	**Average rank Adults (est.age 3 or older)**
Back reef zone (BR)	320	244.58	280.21	326.90
Front reef zone (FR)	320	396.43	360.79	314.10
Test statistic	**-**	**124.90**	**35.25**	**1.27**
P - value	**-**	**0.0 ***	**<0.00001 ***	**0.26**

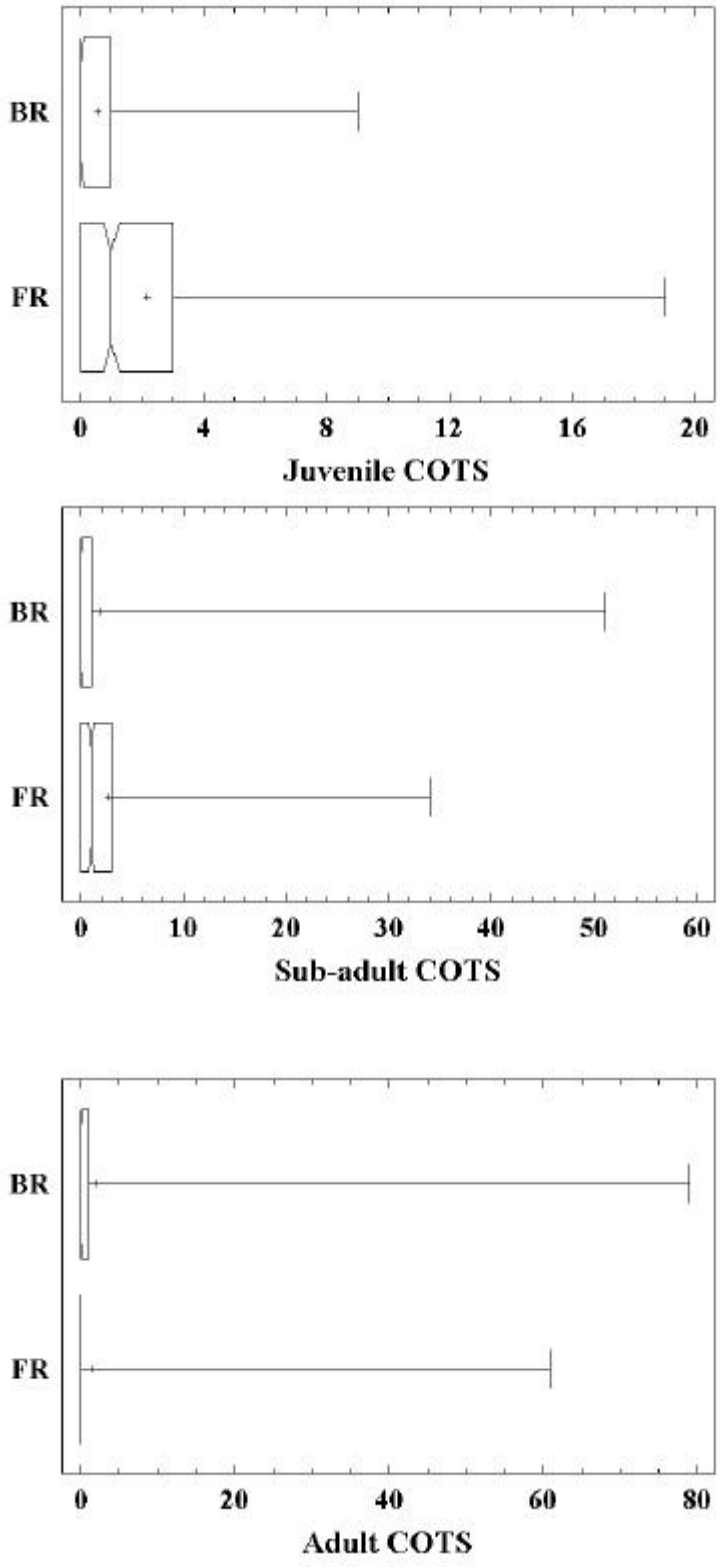


Figure 6. Box-and-Whisker plots showing density distributions of estimated age classes of *A. planci* across two reef zones. Notches were used to assess the differences in median densities (Kruskal-Wallis tests). (+) indicates the mean density for the respective age classes at the zonal scale.

3.3.4 Recent trends in reef status classification

Active Outbreaks (ASO/AO): Almost 40% of survey reefs were recorded with active spot or reef-wide outbreaks in 1999-00.This is 30% below the peak figure recorded during the outbreak activity from 1996-97 to 1997-98 (Fig. 7a). The decline in the proportion of active outbreaks is more pronounced on the nine core reefs (reefs surveyed every year since 1994-95) where only 10% of reef zones and/or reefs remain classified as current active outbreaks. The recent peak in starfish activity occurred in 1996-97 when 100% of these core reefs experienced active outbreaks (Fig. 8a).

Incipient Outbreaks (ISO/IO): Incipient spot and/or reef-wide outbreaks were identified on 60% of reefs surveyed in 1999-00 (Fig. 7b). The proportion of incipient outbreaks within the subset of the nine reefs surveyed every year since 1994-95 was higher, with around 80% of reefs classified as incipient spot and/or reef wide outbreaks (Fig. 8b). Every core reef which is supporting an incipient outbreak has experienced active spot and/or reef-wide outbreaks within the last three or four years.

Post outbreaking reefs (PSO/PO): In 1999-00, there were 30% of post-outbreaking reefs across the survey area which is a similar situation to 1998-99 (Fig. 8c). However, the percentage of post-outbreaks on the subset of nine core reefs declined from around 80% in 1998-99 to approximately 55% in 1999-00 (Fig. 7c). The reduction in the number of reefs classified as post-outbreaking corresponds to an increase in the number of reefs re-classified as incipient outbreaks (Figs. 7b, 8b).

Non-outbreaking reefs (NSO/NO): There were no reefs classified as non-outbreaking, ie. all reefs surveyed in 1999-00 are affected by the current COTS outbreak episode (Figs. 7d, 8d). All 19 reefs surveyed in 1999-00 have experienced, are currently experiencing, or soon will be experiencing spot and/or reef-wide outbreaks. Therefore, there are few mid-shelf reefs which are unaffected by COTS outbreaks. Across the survey area, the proportion of unaffected reefs has declined from 50% recorded in 1997-98, to 10% in 1998-99 and down to 0% in 1999-00 (Fig. 7d).

Table 7. Summary counts of reef classification status as assigned to survey reefs since 1994-95 (complete set of ALL survey reefs).

	Numbers of Reefs					
Reef status	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
AO / ASO	9	13	16	16	10	7
IO / ISO	3	5	0	2	4	9
PO / PSO	0	0	0	1	5	3
NO / NSO	12	4	6	2	2	0
TOTAL	**24**	**22**	**22**	**21**	**21**	**19**

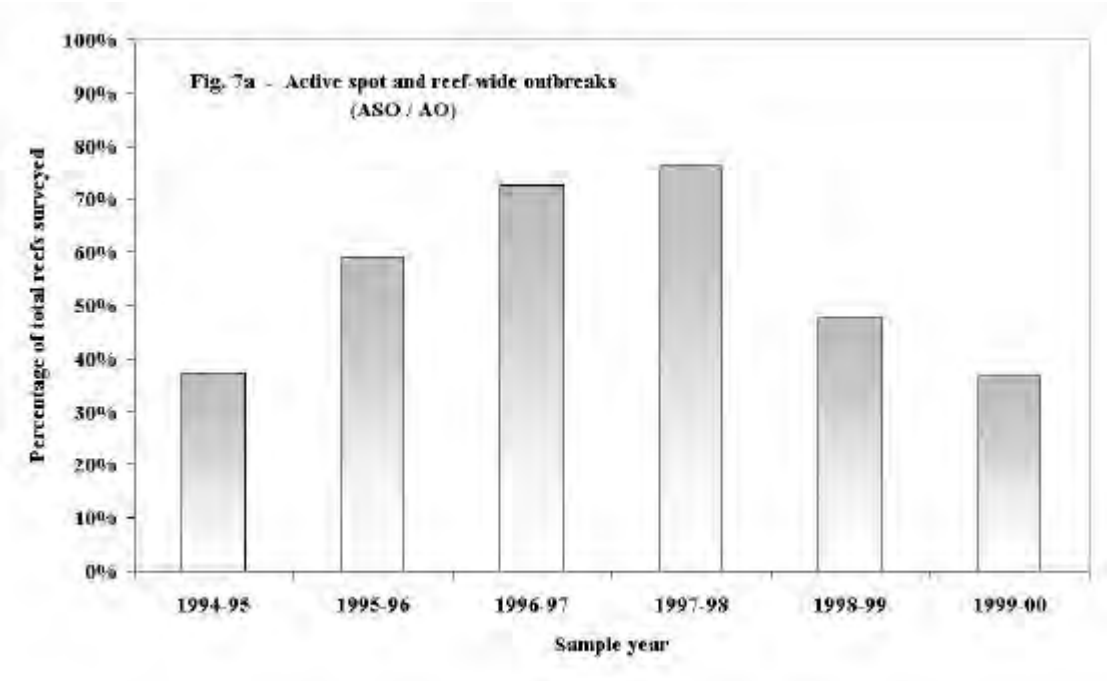


Figure 7a. The percentage of survey reefs classified as actively outbreaking (ASO/AO). (Analysis based on complete set of all reefs surveyed in respective sampling years).

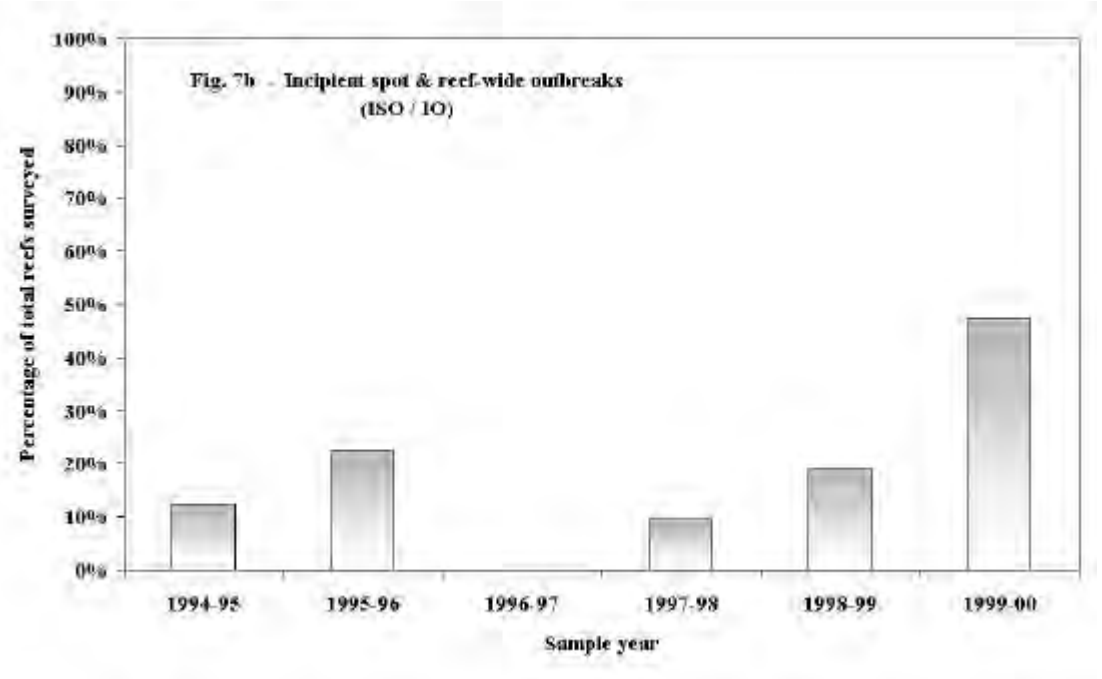


Figure 7b. The percentage of reefs classified as incipient outbreaks (ISO/IO). (Analysis based on complete set of all reefs surveyed in respective sampling years).

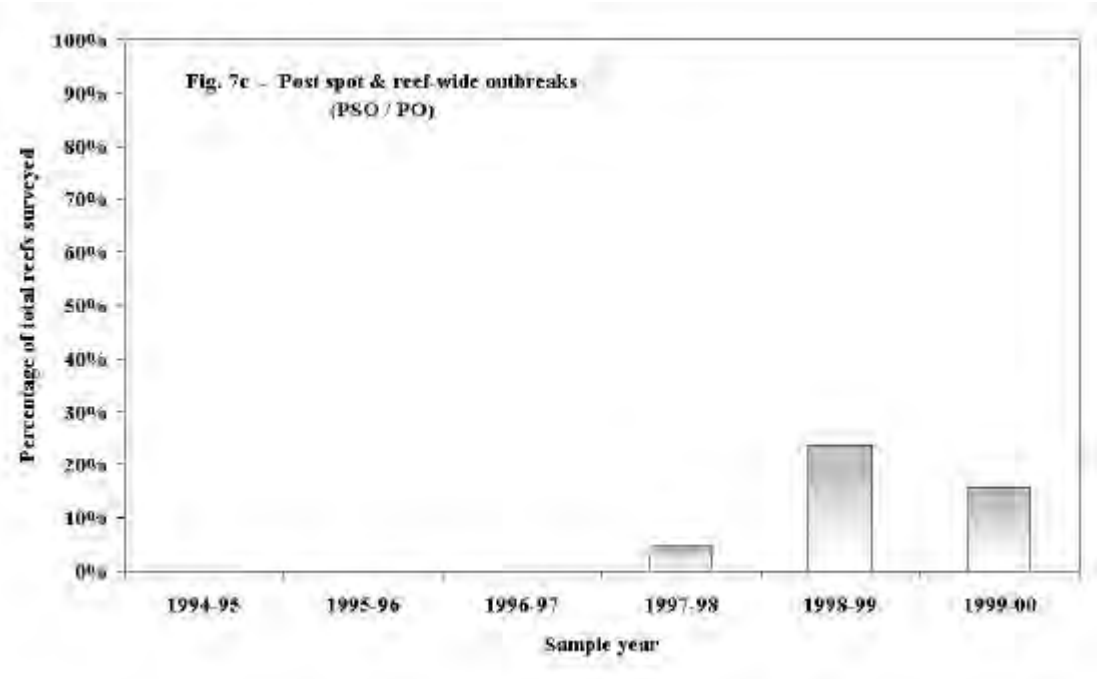


Figure 7c. The percentage of reefs classified as post-outbreaking (PSO/PO). (Analysis based on complete set of all reefs surveyed in respective sampling years).

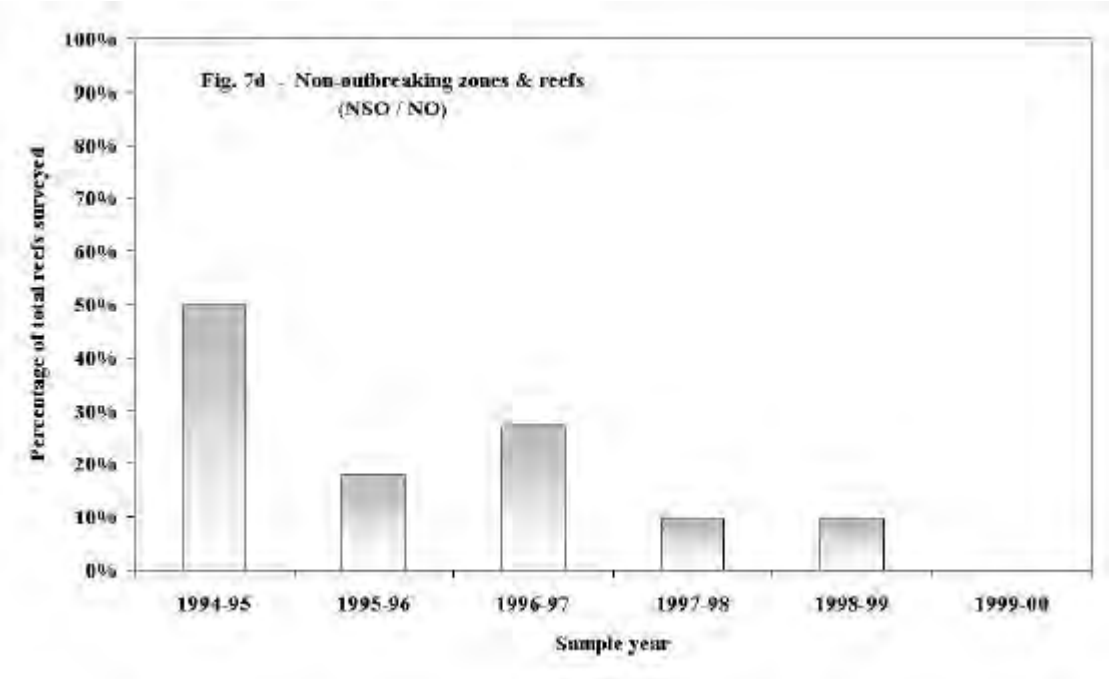
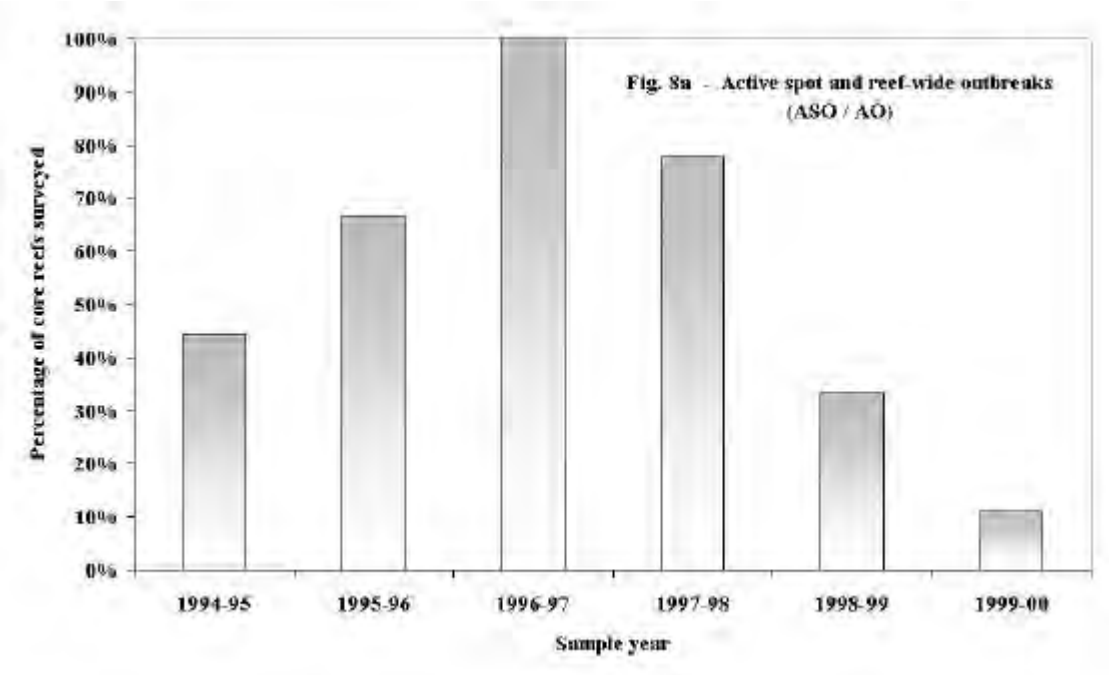


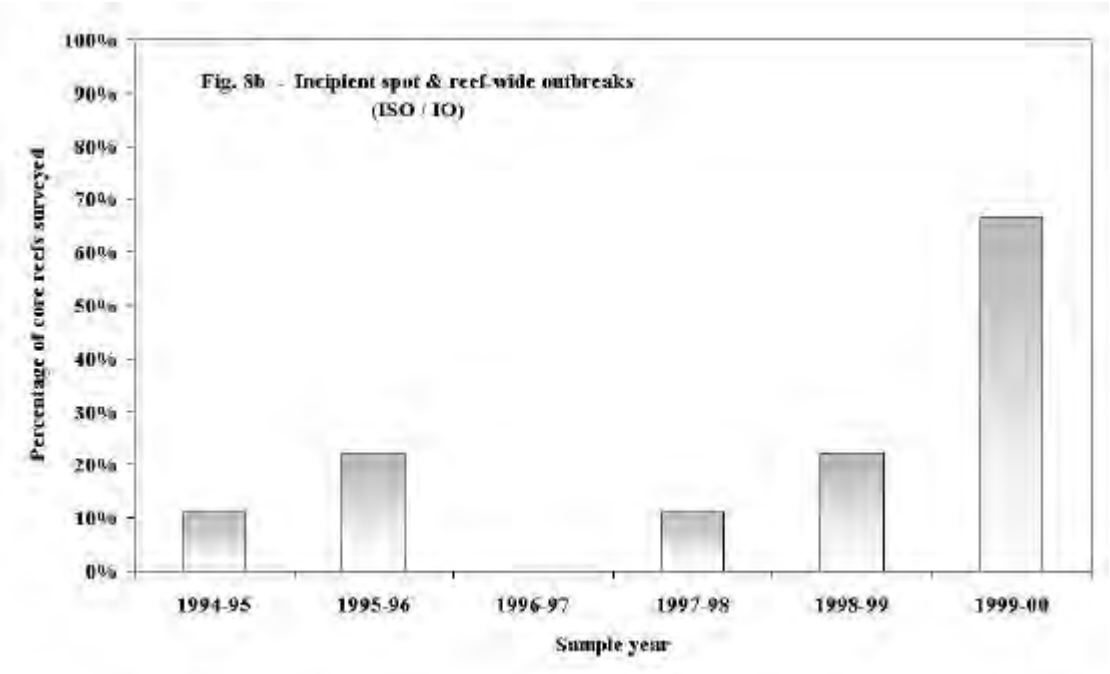
Figure 7d. The percentage of survey reefs classified as non-outbreaking (NSO/NO). (Analysis based on complete set of all reefs surveyed in respective sampling years).

Table 8. Summary counts of reef classification status as assigned to survey reefs since 1994-95 (subset of nine reefs surveyed every year: reefs 14-132b, 15-019, 15-024, 15-070, 15-084, 15-095, 16-023, 16-024, 16-068).

	Numbers of Reefs					
Reef status	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-00**
AO / ASO	4	6	9	7	3	1
IO / ISO	1	2	0	1	2	6
PO / PSO	0	0	0	1	4	2
NO / NSO	4	1	0	0	0	0
TOTAL	**9**	**9**	**9**	**9**	**9**	**9**

Figure 8. Percentage of core survey reefs classified as (**8a**) actively outbreaking (ASO/AO), (**8b**) incipient outbreaks (ISO/IO), (**8c**) post-outbreaking (PSO/PO) and (**8d**) non-outbreaking (NSO/NO). (Analysis based on subset 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, 16-068).





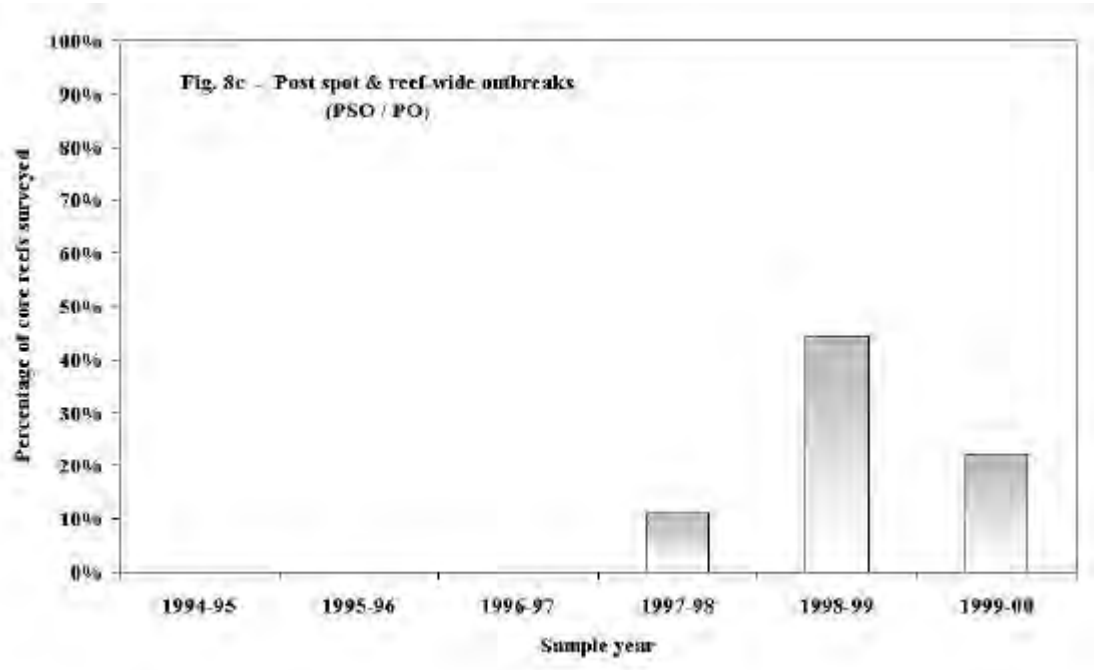


Fig. 8c – Post spot & reef-wide outbreaks
(PSO / PO)
Percentage of core reefs surveyed
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1994-95
1995-96
1996-97
1997-98
1998-99
1999-00
Sample year

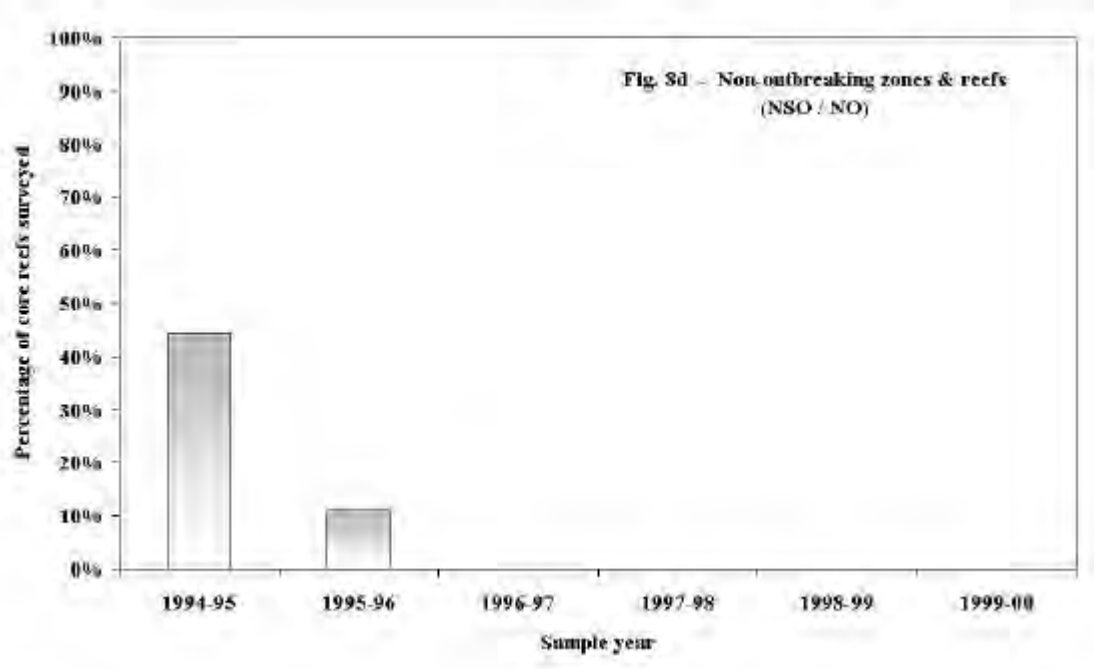


Fig. 8d – Non-outbreaking zones & reefs
(NSO / NO)
Percentage of core reefs surveyed
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1994-95
1995-96
1996-97
1997-98
1998-99
1999-00
Sample year

4. DISCUSSION

Intensive transect-based surveys of crown-of-thorns starfish (*Acanthaster planci*) and associated live hard coral cover (LHCC) conducted in 1999-00 have confirmed the geographically widespread and ongoing nature of the current outbreak episode affecting reefs in the Cairns and central sections of the Great Barrier Reef Marine Park.

1.1 Latitudinal and reef-scale patterns of distribution and abundance

The average density of juvenile *A. planci* (est. age 1) across all reefs surveyed in 1999-00 was 1.34 individuals per 250 m^2, which is the second highest density of juvenile starfish recorded in the six years since the inception of the fine-scale surveys in 1994-95. The highest average density of 3.30 starfish per transect across all reefs was recorded in 1998-99. This was a reliable indication that the current outbreaks would develop throughout much of the survey area. There were significant differences in juvenile densities between survey reefs, however, there was no significant difference in the abundance of this size class between latitudinal bands. Juvenile *A. planci* were found on every reef surveyed this season. This suggests that recruitment in 1998-99 was successful over a wide geographic area and has affected reefs across four degrees of latitude. There are densities of juvenile COTS which indicates a clear potential for further, and in many cases, renewed population increases of *A. planci* in the near future.

Potentially unsustainable juvenile densities were found on reefs which have been affected and unaffected by recent *A. planci* outbreaks. In areas that had suffered significant starfish-induced coral mortality in recent years (i.e. remnant LHCC of <10%), our observations suggest juvenile starfish have a prefernce for the smallest, most recently recruited, hard corals. This suggests that the current starfish cohort could significantly impact the onset and progress of the coral recovery phase on already affected reefs.

As predicted after last year's surveys (see Engelhardt *et al.* 1999), densities of sub-adult starfish (est. age 2) have risen throughout much of the survey area. The 1997-98 cohort (now sub-adult *A. planci)* was the dominant age class recorded in 1999-00 with some 41.5% of starfish (N = 1,659) in this cohort. Combined densities of sub-adult and adult starfish are exceeding threshold levels on 11 (57.9%) of the 19 reefs surveyed, leading to their classification(s) as incipient reef-wide (IO) or incipient spot outbreaks (ISO). It is of particular

concern that incipient outbreaks were identified on 10 mid-shelf reefs that have already experienced COTS outbreaks in recent years. Renewed Outbreaks are developing on these reefs after only three to five years which casts significant doubt over the long-term sustainability of the periodicity of the outbreak phenomenon in the central GBR region. The remnant LHCC on some of these reefs may prevent the maturation of the 1997-98 cohort. However, we observed significant COTS feeding activity on recently recruited hard corals during the 1999-00 surveys which suggests current starfish feeding activity has already impacted on the dynamics of local coral communities.

Densities of adult starfish (est. age 3 or older) exceeded sustainable levels on seven (36.8%) of the 19 reefs surveyed in 1999-00, with two reefs supporting reef-wide outbreaks. Another five of the survey reefs had active outbreaks restricted to either the front- or back-reef zone. Therefore, there is a declining proportion of survey reefs which are classified as actively outbreaking. Since the inception of the fine-scale surveys in 1994-95, the highest proportions of active outbreaks were recorded during the 1996-97 and 1997-98 surveys when some 70% of reefs surveyed supported above-sustainable populations of *A. planci*. Over the last six years, the proportion of reefs classified as actively outbreaking has not dropped below 35% of reefs surveyed.

However, as a result of the ongoing outbreak activity throughout this period, the cumulative total of mid-shelf reefs that have recently (post-outbreak), are currently (active outbreak) or will be (incipient outbreak) affected by COTS outbreaks has reached 100%. Since the inception of the fine-scale surveys in 1994-95 none of the reefs or zones within these reefs which have been surveyed on a regular basis have escaped the effects of the latest COTS outbreak. All fine-scale survey reefs were initially chosen at random and hence are deemed to represent the survey area. Therefore these latest findings suggest that LHCC on virtually all mid-shelf reefs between Lizard Island and Townsville is affected by this phenomenon. Our observations and reports 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 reports have confirmed outbreak activity in parts of the reef that were apparently unaffected during the last outbreak episode in the 1980s, including some of the outer shelf reefs in the Port Douglas and Cairns area.

4.2 Within-reef (zonal) patterns of abundance

Significantly more juvenile (est. age 1, 1998-99 recruits) and sub-adult (est. age 2, 1997-98 recruits) starfish were recorded in the exposed front-reef zone compared with the more sheltered back-reef zone. This supports results of previous studies (Laxton 1974, Moran *et al.* 1985, Engelhardt *et al.* 1999). Juvenile *A. planci* have been found from shallow reef flats (Zann *et al.* 1987, 1990) to deep slopes (Pearson and Endean 1969, Yokochi and Ogura 1987, Doherty and Davidson 1988). We also recorded juvenile *A. planci* on front-reef slopes at depths of between 0.5 and 15 m. However, it remains unclear whether the within-reef patterns of distribution of juvenile starfish are the result of (i) settlement preferences of *A. planci* larvae for exposed front-reef zones, (ii) passive larval dispersal controlled by reef-scale hydrodynamics (Black and Gay 1987, Black 1988), (iii) habitat-related differences in food availability (Yamaguchi 1974, Lucas 1984) or (iv) predator-induced differential mortality rates of juvenile starfish.

In contrast, the within-reef distribution of adult *A. planci* (est. age 3 and older) observed in 1999-00 did not show any significant zonal effect. The uniformity of within-reef distribution of adult starfish contrasts with the findings of most previous studies, including results of previous fine-scale surveys. In 1998-99, we found adult starfish were significantly more abundant in the protected back-reef zones. Larger *A. planci* may move to sheltered waters to reduce susceptibility to strong water movement and risk of dislodgement (Ormond and Campbell 1971, Laxton 1974, Moran *et al.* 1985). Outbreaking populations initially appear in exposed reef-front environments (Pearson 1972, Endean 1976, Birkeland and Randall 1979, Moran *et al.* 1985), but subsequently move into back-reef areas (Laxton 1974, Kenchington 1976, Moran *et al.* 1985). The breakdown of this apparently typical pattern of within-reef distribution of adult *A. planci* may reflect the reduction of LHCC across many COTS-affected reefs, particularly in the protected back-reef zones. We suggest that, as remnant LHCC in back-reef zones becomes insufficient to support existing cohorts of large adult starfish, these populations may be forced to move in search of food. Such forced within-reef migration movements could result in spread of adult starfish across reefs as observed in 1999-00.

The difference in distribution of juvenile and sub-adult starfish identified in 1998-99 and in 1999-00 have important implications for future monitoring of *A. planci* populations. If the objective is early detection of developing outbreaks (forecasting capability), then considerable effort should go into sampling reef-front environments. In contrast, if the main objective is to assess past recruitment events on reefs (hindcasting capability), then both back- and front-reef

zones should be surveyed to gain insight into the probable age structures of local starfish populations.

4.3 Conclusions and recommendations

Intensive fine-scale surveys over the past six years have identified the widespread nature and effects of the current outbreak episode of *A. planci* in the central GBR region. Successful recruitment of starfish appears to have occurred every year throughout the study period. The 1997-98 cohort was one of the largest and geographically widespread age classes of *A. planci* recorded on the GBR. This cohort is approaching maturity and will probably reach its first reproduction by November / December 2000. There is potential for further significant impacts on coral reef communities throughout much of the Cairns and central sections of the GBR Marine Park.

The 1999-00 surveys indicate that some mid-shelf reefs in this region will soon experience renewed outbreak activity, only three to five years after a previous event. The observed dynamics suggest a shift away from the previously observed 15 to 17 year periodicity of outbreak episodes in this region. A significant shortening of periodicity is probably unsustainable in the long-term as hard coral communities on affected reefs would have insufficient time to completely recover and regenerate. Increasingly chronic outbreaks of *A. planci* could result in permanently degraded reef sites which are unable to recover from frequent high-level disturbances. The trends are prominent on reefs located offshore from Port Douglas and Cairns. Therefore, they could have serious implications for the future operations and sustainability of the regional reef tourism industry. Strategic efforts to assess the indications of such trends should be given the highest priority. Intensive fine-scale monitoring of *A. planci* and LHCC should be continued and extended to maximise the chance of identifying signs of further reef degradation and reduced coral recovery in a timely manner.

5. ACKNOWLEDGMENTS

We thank the CRC Reef Research Centre and the Great Barrier Reef Marine Park Authority for providing funding and logistic support for this project. We are also grateful for the assistance and support provided by the crew of M.V. Floreat, in particular, the owner/skipper, Mr Markus Oke, and our on-board chef, Mr Alfredo Torrisheba.

We gratefully acknowledge the guidance, encouragement and expertise provided over many years by the past members of the Crown-of-Thorns Starfish Research Committee (COTSREC). Without the support and assistance kindly offered by many Committee members, in particular Dr Brian Lassig (Environment Australia), Professor Graham Mitchell (Foursight Pty Ltd), Mr Bob Pearson (QDPI) and Dr Keith Sainsbury (CSIRO), this project would not have been possible.

Our sincere thanks also to the two anonymous reviewers of this report. Their respective comments and suggestions are greatly appreciated.

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APPENDIX A

The classifications of survey reefs with regard to outbreaks of *A. planci*.

Table 9. The 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 and the Great Barrier Reef Marine Park Authority 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 stated).

GBR Reef ID	Reef Name	Status 1994-95	Status 1995-96	Status 1996-97	Status 1997-98	Status 1998-99	Status 1999-00
14-116	Lizard Island Reef [1]	AO	NS	NS	NS	NS	NS
14-143	Nth. Direction Reef [1]	ASO(BR) ISO(FR)	AO	AO	NS	NS	NS
14-132b	Rocky Islets Reef (b)	IO	AO	AO	AO	PO	PO
14-133	U/N [2]	IO	AO	NS	AO	NS	NS
15-019	Long Reef	ASO(BR) NSO(FR)	AO	AO	ASO(BR) PSO(FR)	IO	IO
15-024	Mackay Reefs	ASO(BR) NSO(FR)	AO	AO	AO	ASO(BR) PSO(FR)	IO
15-033	Lark Reef (E) [5]	NO	ASO(BR) ISO(FR)	ASO(BR) NSO(FR)	ASO(BR) NSO(FR)	NS	NS
15-043	U/N [2]	IO	IO	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
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)
15-089	Endeavour Reef (E) [5]	ASO(BR) NSO(FR)	ASO(BR) ISO(FR)	ASO(BR) ISO(FR)	ASO(BR) ISO(FR)	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)
16-015	Mackay Reef [1]	ASO(BR) NSO(FR)	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)
16-024	U/N	NO	IO	AO	AO	PSO(BR) FSO(FR)	PO
16-026	Tongue Reef (W) [3]	NO	NS	NS	NS	NS	NS
16-026	Tongue Reef (E) [3]	NS	ASO(BR) NSO(FR)	NSO(BR) NS(FR)*	NS	NS	NS
16-057	Hastings Reef [4]	NO	NO	NS	NS	NSO(BR) FSO(FR)	NS
16-060	Michaelmas Reef [6]	NS	NS	NS	NS	ISO(BR) FSO(FR)	NS
16-064	Arlington Reef (W) [3]	NSO(BR) ASO(FR)	NS	NS	NS	NS	NS
16-064	Arlington Reef (E) [3]	NS	ASO(BR) ISO(FR)	ASO(BR) NS(FR)*	NS	NS	NS
16-049	Green Island Reef [1]	NO	IO	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)
16-071	Moore Reef [6]	NS	NS	NS	NS	ASO(BR) FSO(FR)	NS
16-073	Elford Reef (E)	NO	NO	NSO(BR) NS(FR)*	NSO(BR) NS(FR)*	NS	NS
17-001	Sudbury Reef [3]	NO	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)
17-006	Maori Reef [3]	NO	NS	NS	NS	NS	NS
17-011	Coates Reef	NS	AO	AO	AO	PSO(BR) NS(FR)*	PO
17-014	Hedley Reef [7]	NS	NS	NS	ASO(BR) NS(FR)*	NS	NS
17-016	McCulloch Reef [3]	NO	NS	NS	NS	NS	NS
17-023	Cayley Reef	NS	NS	AO	ASO(BR) ISO(FR)	ASO(BR) NS(FR)*	PSO(BR) ISO(FR)

17-034	Feather Reef	NS	NO	NO	ISO(BR) NSO(FR)	ASO(BR) ISO(FR)	AO
17-047	Eddy Reef [4]	NS	NS	NSO(BR) NS(FR)*	NS	AO	AO
17-051	Beaver Reef [7]	NS	NS	NS	NS	NS	ASO(BR) NS(FR)*
17-064	Taylor Reef [4]	NS	NS	NSO(BR) NS(FR)*	NS	ASO(BR) ISO(FR)	ASO(BR) NS(FR)*
18-026	U/N [3]	NS	NS	NSO(BR) NS(FR)*	NS	NS	NS
18-030	Kelso Reef [5]	NS	NS	NS	ISO(BR) NSO(FR)	NS	ASO(BR) NS(FR)*
18-031	Little Kelso Reef	NS	NS	NS	ASO(BR) NSO(FR)	ASO(BR) NSO(FR)	ISO(BR) ASO(FR)
18-075	John Brewer Reef	NS	NS	NS	NO	NO	IO
18-078	Lodestone Reef	NS	NS	NS	ASO(BR) NSO(FR)	PSO(BR) ISO(FR)	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 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 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 one-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 to (i) either replace previously sampled reefs or (ii) geographically expand the survey area, were selected at random.

GLOSSARY

AO	Active Reef-wide Outbreak
ASO	Active Spot Outbreak
BR	Back Reef
COTS	Crown-of-Thorns Starfish
COTSREC	Crown-of-Thorns Starfish Research Committee
FR	Front Reef
FSO	Future Spot Outbreak
GBR	Great Barrier Reef
GBRMP	Great Barrier Reef Marine Park
GBRMPA	Great Barrier Reef Marine Park Authority
IO	Incipient reef-wide Outbreak
ISO	Incipient Spot Outbreak
LHCC	Live Hard Coral Cover
NO	Non-outbreaking Reef
NS	Not Surveyed
NSO	No Spot Outbreak
PO	Post Outbreaking
PSO	Post Spot Outbreak
SE	Standard Error