CRC REEF RESEARCH TECHNICAL REPORT

DEVELOPMENT OF COST-EFFECTIVE CONTROL STRATEGIES FOR CROWN-OF-THORNS STARFISH

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FOREWORD

Control of Crown-of-thorns starfish has been an important issue for reef managers for over 30 years. There are no methods which can be applied to intense starfish populations affecting large areas of reefs but tactical controls to retain corals at sites important for tourism and recreation are feasible and often recommended.

Control programs involve a substantial commitment of trained effort over a long period. This report documents practical research which enables managers and planners of control programs to appreciate the scope, commitment and limitations of effective field operations. It is an important and practical management support document applicable to coral reef environments throughout the Indian and Pacific Oceans.

Richard Kenchington
Executive Director
Great Barrier Reef Marine Park Authority

EXECUTIVE SUMMARY

Crown of thorns (COTS) eradication effort was carried out by injection of Dry Acid (Sodium Bisulphate solution). Three injection regimes were tested at two different reefs (Lizard Island and Green Island) for their effectiveness in reducing COTS densities on small patch reefs. The effect on coral community structure of altering COTS densities was also investigated.

Key Results

1. Over a 10-month period at Lizard Island, two injection regimes (high frequency-low intensity, and low frequency-high intensity effort) significantly reduced COTS densities.

2. At Lizard Island, high frequency/low intensity effort was more effective over the longer term at reducing coral impacts than a low frequency/high intensity treatment. However, hard coral cover decreased at a steady rate in both treated and untreated sites. This was postulated to be due to the continual influx of COTS immigrants from elsewhere. In contrast, a standardised index of the amount of coral damage (complete and partial mortality), significantly increased in the untreated sites compared to the treated sites, indicating that the treatments were halting the expected decline in coral cover at these sites.

3. At Green Island, a similar high frequency/low intensity treatment regime and an additional high intensity treatment regime did not significantly reduce COTS densities. Unexpected factors prevented the analysis of impacts on the coral community as proposed. However, valuable descriptive assessments of impacts are presented in the appendices.

4. Migration of COTS into both Lizard and Green Island study sites was postulated to be negating the effect of protective measures over longer periods. Consequently, eradication procedures appeared to be stemming the rate of decline but not the net decline in coral cover.

5. Diver experience was also found to be an important factor in the effectiveness of a control program. Greater diver experience both with diving in general, and with finding cryptic COTS in particular, resulted in higher numbers of COTS injected per unit time.

Recommendations for Control Programs for Industry

Note : The following recommendations are based on results contained in this report and additional observations made during the study.

1. Successful control programs require : (1) constant eradication effort over relatively long periods of time; (2) maintenance of the focus on the target area and avoidance of the inclination to apply effort on higher concentrations of COTS outside the target area; (3) treating COTS concentrations in off-site areas in a strategic manner if there is potential for migration into the target area; (4) maintenance of medium term vigilance of the local situation (in terms of years), until the threat is passed; and, (5) ensuring that the ability to alter the intensity of eradication efforts at short notice is retained.

2. It is essential to have knowledge of the COTS outbreak situation beyond the boundaries of the desired area of protection because migration of COTS from adjacent areas will dictate the type and amount of eradication effort.

3. The interval between eradication visits at any site should be determined on a case by case basis. The required degree of eradication effort is a function of the unique situation associated with each area of reef requiring protection, and no single strategy will be applicable in all outbreak situations or reefs, or at all phases of an outbreak on one reef.

4. However, as a starting point, it is recommended that an intensive eradication effort in the initial phases of a control program be followed by frequent less intensive effort and that only well trained competent divers are used.

1. OBJECTIVES, MANAGEMENT IMPLICATIONS AND INDUSTRY IMPLICATIONS

Task Objectives

1. To test the effectiveness of commonly used injection regimes on the density of COTS; and,

2. To investigate the impact of the COTS eradication programs on the local coral communities.

Management Implications

The results of this study indicate that a single control regime (using the injection technique tested here) will not be effective in all COTS situations.

Under the densities of COTS encountered in this study, the most intensive control measures tested here will at best stem the rate of decline in live coral cover, but not eliminate all impacts on corals.

Industry Implications

A long term commitment to maintaining a control program is the only chance of protecting key sites from long term COTS damage.

An employment performance indicator, or judging an employee's worth, should not be based on the gross number of COTS killed each day, but on the effectiveness of protecting the visual appeal of a key site.

Personnel experience in COTS control measures is an invaluable resource for industry.

(**Note** : A full discussion of the above implications are presented in Appendix 7)

2. INTRODUCTION

Control programs for the protection of small areas of reef (1-2 ha) from aggregations of COTS have met with mixed success in the past. Birkland and Lucas (1990) provide a good summary and assessment of past efforts. They concluded that the requirements of a successful control program include the following: (i) **advanced warning** of an impending threat to an area whereby a counter response can be mounted prior to the problem becoming apparent within the desired area of protection; (ii) a **rapid response** in cases where the primary motivation is to protect a specific coral community; (iii) sufficient **available personnel** who can be mobilised at short notice, though the authors noted that for very large aggregations unrealistic numbers of divers would be required to have an effect on COTS densities; and, (iv) knowledge of the **degree of aggregation** of COTS which will determine the efficiency of the control program.

Control methods for removing COTS from reefs have focused on specific and non specific chemical and physical means. GBRMPA have completed trials of certain methods and concluded that injections of ‘Dry Acid’ (sodium bisulphate) fulfilled the majority of requirements of an effective low cost control method (Lassig 1995).

This project aimed to experimentally assessing the effectiveness of COTS control measures on small reefs using injection guns filled with a solution of ‘Dry Acid’. To date, no information is available on the most efficient way of carrying out small scale eradication programs using this technique. A number of relevant factors needed to be taken into account, including habitat type (eg., patch reefs verses continuous reef edges), the density and size class structure of COTS, the type of coral community, and the frequency and intensity of injection programs. Practical recommendations for commercial operators with regard to factors such as the best search method, and ways to maintain efficiency as COTS densities drop, were objectives of the study.

COTS appear to have size specific feeding behaviour (Birkland and Lucas 1990), but this is also determined by COTS densities, and whether or not they are aggregated. The impact on coral communities of this complex relationship has not been clearly worked out at present. It is likely that these feeding and behavioural shifts will result in different impacts on the structure of local coral communities. There appears to be a change in feeding behaviour when a threshold of feeding activity is reached or possibly when the food supply is dwindling rapidly. This change can occur with a switch to seemingly constant feeding activity in the daytime from more irregular cryptic night time feeding (Moran 1986). Both a dwindling food supply and an influx of individuals from elsewhere can trigger aggregation and more or less continuous feeding responses.

Using detailed fine-scale surveys, an active COTS outbreak was detected on Lizard Island in October 1994 and the beginnings of an incipient outbreak at Green Island in February 1996 (Engelhardt et. al. 1997). The detection of these outbreaks provided a timely opportunity and accessible location to test the effectiveness of different treatment regimes in controlling COTS. Choice of treatment regimes was influenced by the ability of tour operators to accommodate control programs within their normal work day routines.

This project was divided into two study phases, which were conducted at two separate reefs. Phase I, at Lizard Island, was followed by phase II at Green Island reef. COTS aggregations had been present at Lizard Island for a year or more prior to the commencement of this study. In contrast, COTS aggregations were first observed less than six months prior to the start of field work on Green Island.

PHASE I (1995 - 1996) : LIZARD ISLAND

3. METHODS : LIZARD ISLAND

Three survey trips were conducted at Lizard Island in October 1995, February 1996, and June 1996. A fourth trip in August 1996 was incorporated to assess the effects of a biweekly injection regime on two of the study reefs.

Six reef sites were chosen for study. All sites were located on the leeward side of Lizard Island on the western edge of the lagoon (Figure 1). Three sites were approximately 2 hectare portions of larger patch reefs and 3 sites were separate patch reefs of approximately similar size. Sites were chosen on the basis of being essentially the same habitat type with similar COTS densities and coral community type. Also, practical considerations influenced the selection of sites, particularly in relation to accessibility and ease of identification of the exact locations.

Figure 1. Air photo of Lizard Island showing the location of study sites. Sites #1 and #2 are the weekly injection sites, #3 and #6 are the 4-monthly injection sites, and sites #4 and #5 are the non treatment sites. The edge of Palfrey Island is on the left hand side of the photo while a part of Lizard Island is shown in the bottom right hand corner. Due north is approximately towards the RHS of the photo.

Two sites (sites #1 and #2) were visited weekly for the first ten weeks, and then every two weeks during the following twenty weeks. For each visit, two person-hours of injection effort was used at each of these sites. Every four months at another two sites (sites #3 and #6), injection effort was continued until the number of injected COTS levelled off to nearly zero. Two reef sites were also used as (non-treatment) control sites (#4, #5) where corals and COTS were surveyed at the same time as the 4-monthly injection sites.

At each site and at each 4-monthly visit, COTS densities, live coral densities, frequencies of coral fragmentation, and live and dead coral cover were estimated prior to the injection of COTS. During each survey, four randomly placed tapes were laid out within the same area of previous surveys at each site, the number of COTS in belt transects were counted, and their maximum diameters measured. Belt transects for COTS estimates were 50 m by 5 m.

Coral cover was estimated from the same tapes set out for the COTS surveys. Percent cover was calculated from line intercept records of the first 30 m of each transect.

Analysis of COTS treatment effects on coral community indices was by ANOVA (the model included the fixed effects of treatment, survey, and sites nested within treatments), using percent cover of a range of coral taxa and dominant growth form types (for both live and dead standing coral). The SURVEY x TREATMENT interaction term was the source of variation that was of interest in this study. A mortality index, calculated as a ratio of dead to total (live + dead) coral cover, was used as a measure of impact of COTS on coral community structure. The index standardises the degree of coral cover reduction across sites with varying initial coral cover. COTS densities were analysed in the same way as the coral data. Bartlett's test for homogeneity of variance was applied in all univariate tests. Where there was a significant ANOVA result, Tukey's post hoc tests was used to determine which treatments were different to each other, at the beginning and end of the study. Log(x+1) transformations were applied to COTS frequency data to improve the homogeneity of variances. In all other cases, transformations were not applied. ANOVA were run using the SYSTAT program (Wilkinson 1990).

Non metric multidimensional scaling (MDS) analysis using the relative abundance of coral species were used to investigate patterns of change in community structure over the study period. The Bray Curtis similarity index was used to produce a distance matrix which is analysed by non-metric MDS techniques (Primer Programs, Plymouth Marine Labs).

Guidelines for publishing CRC Technical Reports stipulate that any descriptive, non statistically validated, or anecdotal information is not presented in the main body of the text. Because of the nature of the study and the importance of all types of information to industry, we have included all such information in appendices.

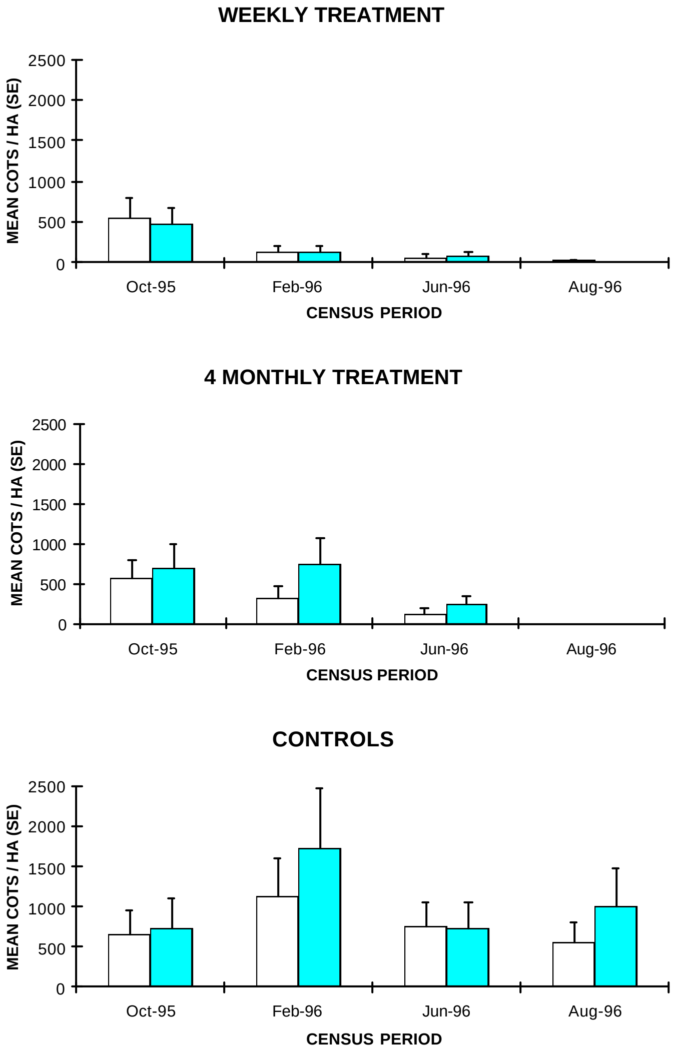


Figure 2. Lizard Island : Mean densities of COTS per hectare estimated from four (50 m x 5m) belt transect surveys. The same treatment pair of sites for each census are shown along side each other as clear and shaded bars. Densities of COTS were converted to hectares by multiplying the COTS recorded in each belt transect by forty. Weekly and 4monthly treatments refer to different visit intervals and to different intensities of removal effort, while non injection controls provided a comparison to the injection treatments (see methods). Only weekly and control sites were surveyed in August 1996.

4. RESULTS : LIZARD ISLAND

COTS Densities (October 1995 - June 1996)

Densities of COTS varied significantly between treatments over time (SURVEY x TREATMENT interaction term, ANOVA, Appendix 1). Tukeys tests showed no significant differences between treatment groups in the beginning (October 1995), but significant differences between controls and weekly treatments (P = 0.001), and controls and 4-monthly treatments (P = 0.014) in June 1996. Clear trends in COTS densities can be seen in Figure 2, where similar mean densities in all treatment groups at the beginning of the study are contrasted with the end of the study, where the non treatment control sites contained higher densities than the two injection treatment sites.

COTS Densities (October 1995 - August 1996)

The ANOVA results from the four surveys (which included an increase to two visits per week to the weekly treatment sites from June to August 1996) showed a significant SURVEY x TREATMENT term (Appendix 2), indicating that the COTS densities in sites within each treatment (weekly and non treatment control groups only) were varying differently to each other. This was predominantly the case in the control sites, where densities appeared to fluctuate independently of each other (Figure 2). The weekly treatment sites both showed uniform reductions in densities over time. Tukey's test showed significantly higher COTS densities in the control sites compared to the weekly treatment sites in both June and August 1996.

Coral Cover (October 1995 - June 1996)

Percentages of live and dead coral cover is shown in Figures 3 and 4. A significant SURVEY x TREATMENT term (ANOVA, Appendix 1) indicated that total live coral cover of sites varied across surveys. The weekly sites generally showed a uniform decrease in cover of total hard coral, whereas cover within sites with the 4-monthly and control treatments fluctuated in non-uniform patterns (Figure 3).

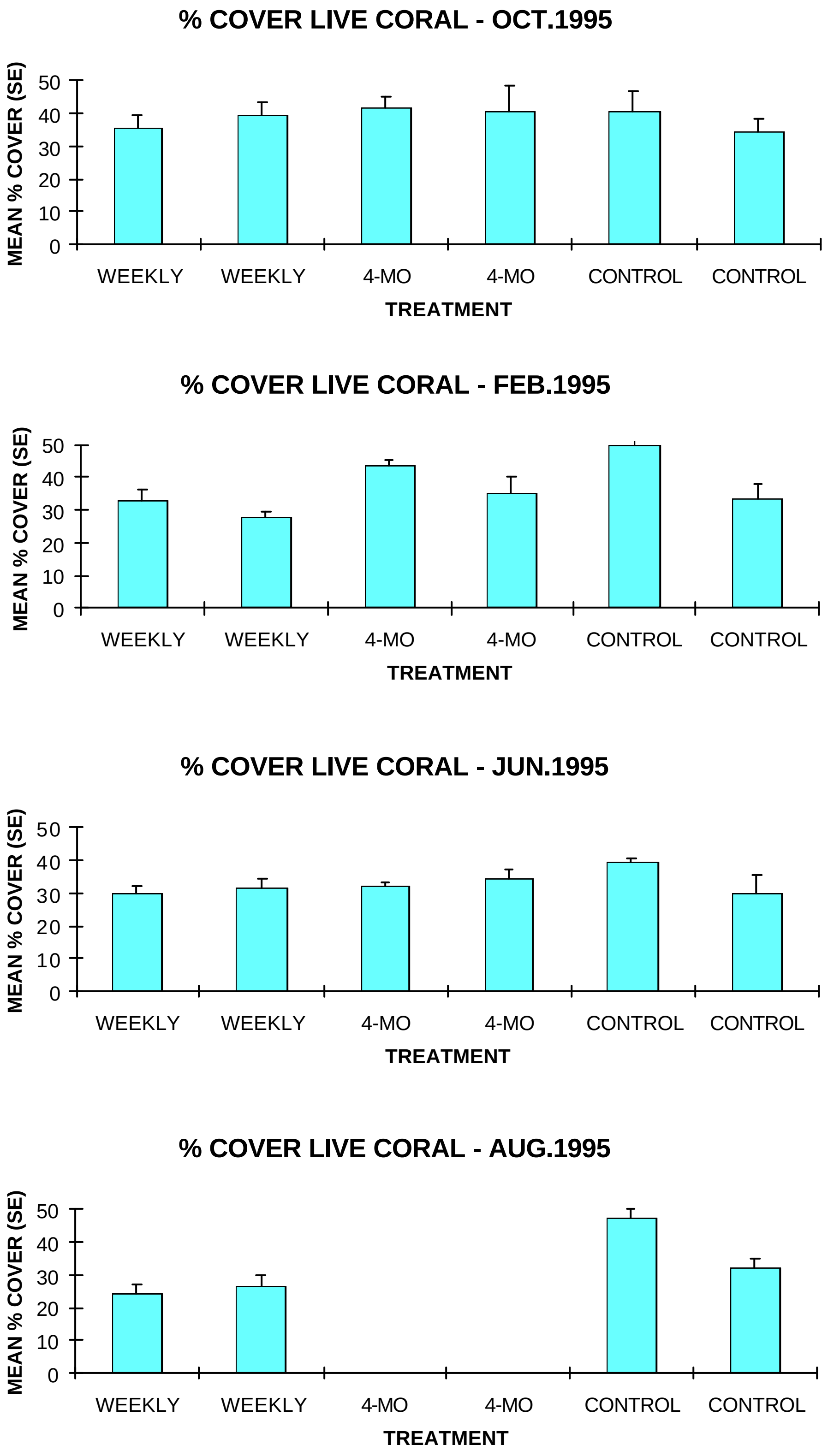


Figure 3. Lizard Island : Mean % cover of live coral from October 1995 to August 1996. The 4-monthly sites were not surveyed in August 1996.

There were no significant changes in dead coral cover among treatments over time (ANOVA, Appendix 1). Also, there were no significant changes in pooled dead *Acropora* spp. (ANOVA, Appendix 1). In comparison, dead tabulate *Acropora* spp. cover changed significantly among treatments over time (Appendix 1). Tukey’s test showed significant decreases in dead tabulate *Acropora* spp. occurred in the 4-monthly treatment sites between October 1995 and June 1996.

The mortality index (the ratio of dead coral cover to total (dead plus live) coral cover) showed significant differences among treatments over time (ANOVA, Appendix 1). Tukey’s test showed that a significant increase in mortality index occurred between October 1995 and June 1996 in the non treatment (controls) sites (Figure 4). Thus it appears that COTS treatments reduced the impact of COTS on coral cover as measured by the mortality index.

Coral Cover (October 1995 - August 1996)

Total hard coral cover of sites varied across surveys (ANOVA, Appendix 2). Cover in the weekly treatment sites generally decreased in a similar pattern over time, but cover of both indices in one of the control sites (#3) alternately increased or decreased at each survey time. Combined *Acropora* spp. showed no significant change in cover among treatments over this time period (ANOVA, Appendix 2). The significant SURVEY x TREATMENT term from the combined *Acropora* spp. ANOVA indicates that there were differences between sites across surveys.

Cover of total dead coral and all dead *Acropora* spp. showed no significant differences among treatments over time (ANOVA, Appendix 2).

The mortality index showed a significant change among treatments over time (ANOVA, Appendix 2; Figure 4). This reinforces a similar result from the October 1995 to June 1996 analysis above though the 4-monthly treatment data was not used in the October 1995 to August 1996 analysis. Tukey’s test and Figure 4 show that the mortality index in the controls increased significantly among surveys while the mortality index from the weekly treatment sites did not change.

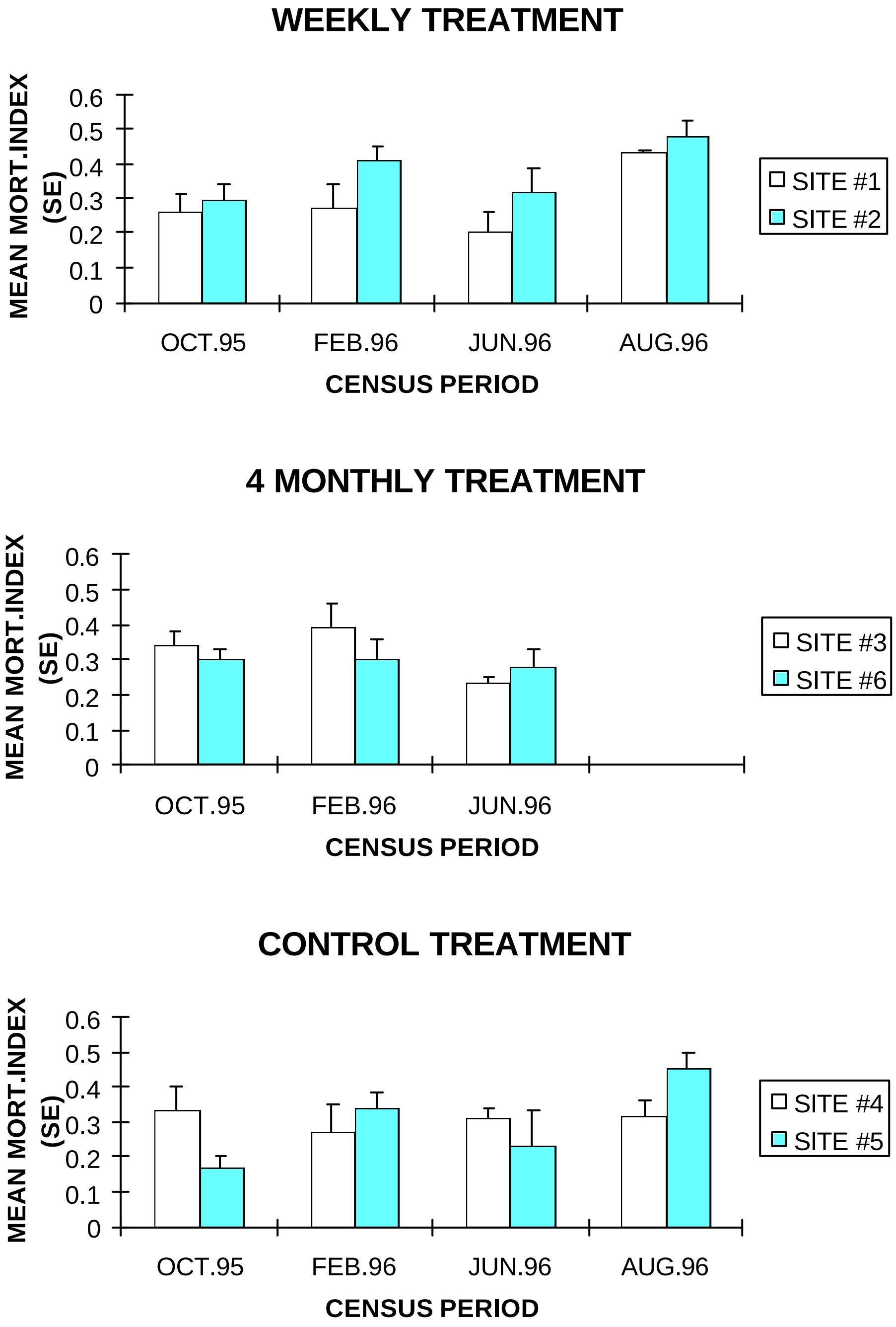


Figure 4 Lizard Island : Mean mortality index for each treatment site and for each survey.

5. DISCUSSION : LIZARD ISLAND

Effectiveness of Treatment Regimes

Both injection regimes significantly reduced the densities of COTS after an eight month period. Short term lower mean COTS densities were observed as a result of intensive 4-monthly treatments in the first 8 month period, though COTS densities increased by the following visit four months later. In contrast, weekly treatment over time resulted in consistently lower COTS densities. Increased injection effort for a further two months (from June 1996 to August 1996) at the weekly treatment sites significantly reduced COTS numbers to levels lower than the preceding period, though complete elimination of COTS was not achieved. In conclusion, the results of this study indicate that an effective strategy of controlling COTS numbers in areas with existing high COTS densities is to apply an intensive eradication effort initially and to follow up with frequent, less intensive effort.

Four months after the initial treatment visit in October 1995, the average density of COTS at the 4-monthly sites had increased to similar levels recorded at the beginning of the study. High COTS densities were also found at the third eradication visit in June 1996, though there was a decrease in density at this final sampling period. There are three possible explanations for this pattern: (i) net immigration as observed above, (ii) very cryptic behaviour, and (iii) inefficiencies in individual diver search and injection effort.

There will always be a certain number of COTS which elude any search effort because of their cryptic behaviour. Also, a few cryptic individuals may survive injection as it was sometimes difficult to inject them in sufficient places, but this small number would not be expected to affect the results. This leaves net immigration as a possible explanation of the difference between post-injection density at one sampling period, and pre-injection density at the subsequent sampling period.

At the frequently-visited sites, the time constraint of one hour per visit for two divers would also ensure that COTS still remained at the sites after the early sampling periods. However, in the absence of recruitment and assuming success of the injection technique, the density of COTS would be expected to approach zero and remain there within the period of the study if migration was not occurring. Transect counts show that COTS density at these sites has approached zero but has never reached it at any stage of the study.

Effects on Coral Communities

Total hard coral cover generally decreased between October and June at all sites. The fluctuating profiles of coral cover over time at some sites were probably due to the patchiness of live coral cover and variations in the random placement of the transect tapes.

The use of the mortality index is a more appropriate measure than the % cover term (for both live and dead coral) as it standardises changes in live coral, thereby allowing for a more powerful comparison of change. The trends of little change or a small increase in the mortality index at all sites indicate that the injection regimes were effective in halting the expected decrease in coral cover under the prevailing circumstances of COTS densities and migration rates.

Figure 5. Air photo of Green Island cay and adjacent reef showing the location of study sites. Sites #1 and #2 are the weekly injection sites, #3 and #4 are the '2-monthly' injection sites, and sites #5 and #6 are the non treatment sites. Due north is approximately towards the RHS of the photo.

PHASE II (1996 - 1997): GREEN ISLAND

6. METHODS : GREEN ISLAND

Survey methods used at Green Island were similar to those used in the Lizard Island study, but one of the injection regimes was modified. The time interval between high intensive COTS eradication visits was reduced from 4 to 2 months, and was coupled with a weekly (2 person/1hr) injection effort as well. The high intensive treatment involved continual injection effort by 2 divers until COTS were reduced to densities such that more than an hour of searching was required before any un-injected COTS was found. This regime was tested because the results from the first phase based at Lizard Island indicated that a shorter time interval between intensive eradication visits was more effective in protecting corals, and it appeared that an additional weekly eradication regime could prevent sharp rises in COTS numbers between the 2 monthly visits. Because the outbreak at some Green Island patch reefs was at an earlier phase than that at the Lizard Island patch reefs, it was decided to re-test the weekly (low intensity/high frequency) regime in this different COTS situation.

Six patch reefs or parts of patch reefs in the back reef area were chosen as study sites (Figure 5). These sites are also the focus of tourist activities such as coral viewing from glass bottom boats, diving, and snorkelling. Intensive eradication treatment was carried out at two sites (#3, #4) at 2 month intervals in addition to approximately weekly treatments (two person hours effort per week) at the same sites. Two sites (#1, #2) were treated for approximately two person hours per week only, and two sites were designated as non treatment or control sites (#5, #6). The weekly eradication work was carried out by Great Adventures Pty Ltd staff at three of the sites (#1, #2, #3) and by Ocean Free Pty Ltd staff at one site (#4).

Unfortunately, a number of factors did not allow statistical analysis of the experimental design as had been originally intended. These factors were : insufficiently detailed information on site locations where COTS were injected by participating industry staff; too broad estimates of COTS sizes from the collaborating stakeholder staff undertaking the weekly treatment program; no written records of weekly eradication effort at one of the 2-monthly treatment sites (#4), though personal communications with the relevant staff indicated that irregular but substantial effort was being applied; occasional injection visits were also undertaken by industry staff at both of the designated non treatment control sites; and, there was significant destruction of corals at many of the study sites by cyclone “Justin” in March 1997.

Although the experimental injection data were questionable due to the enthusiastic but less rigorous participation of industry staff, the categorisation of sites according to the original experimental design was nonetheless adhered to, but few statistical analyses were carried out. Instead, descriptive treatment of the data was preferred and individual comparisons were made between each of the study sites, which were categorised into the three treatment groups. The results of this work are presented in Appendix 5. The only statistical analyses used here was ANOVA of COTS densities, testing for differences between treatments over time (SURVEY x TREATMENT interaction). Although the treatment of weekly sites was more irregular than expected, when coupled with the regular 2-monthly treatment, it was thought that an estimate of the effectiveness of these unplanned treatment regimes was warranted.

7. RESULTS : GREEN ISLAND

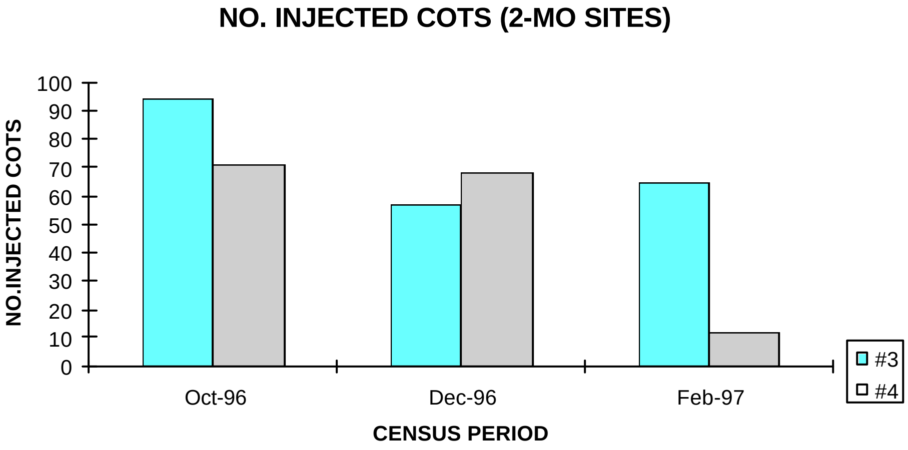
COTS Densities

Trends in mean COTS densities (estimated from belt transects) at each of the treatments sites are shown in Figure 6. Most sites appeared to show minor reductions in mean density by the end of the study period. However, trends were inconclusive and differences between treatments were not significant (ANOVA, SURVEY x TREATMENT interaction term, Appendix 3), when sites were grouped into the different treatment regimes as defined in the initial sampling design.

Although the treatments did not show significant differences in COTS densities over time, the general downward trend in site #4, coupled with the decrease in the number of COTS injected per unit effort at some other sites as well (Figure 7), suggests that the eradication effort was gradually taking effect.

Bimonthly injection effort coupled with weekly treatments appeared to be effective (within four months) in reducing the number of COTS which were found and injected at site #4 in particular (Figure 6 (top, bottom)). An apparent increase between December 1996 and

February 1997 in COTS in site #3 (Figure 7 (middle), Figure 6 (bottom)) was possibly due to migration into this site as it is relatively closer to the large southern slope COTS group than site #4 (pers. comm. Great Adventures staff).



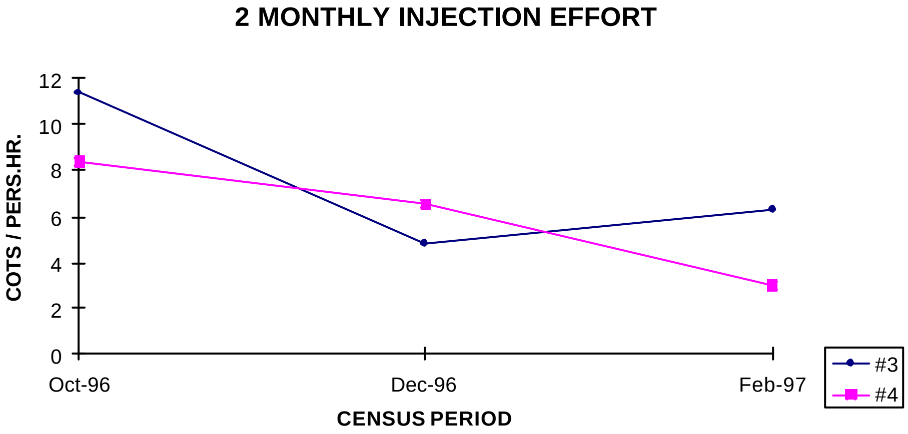
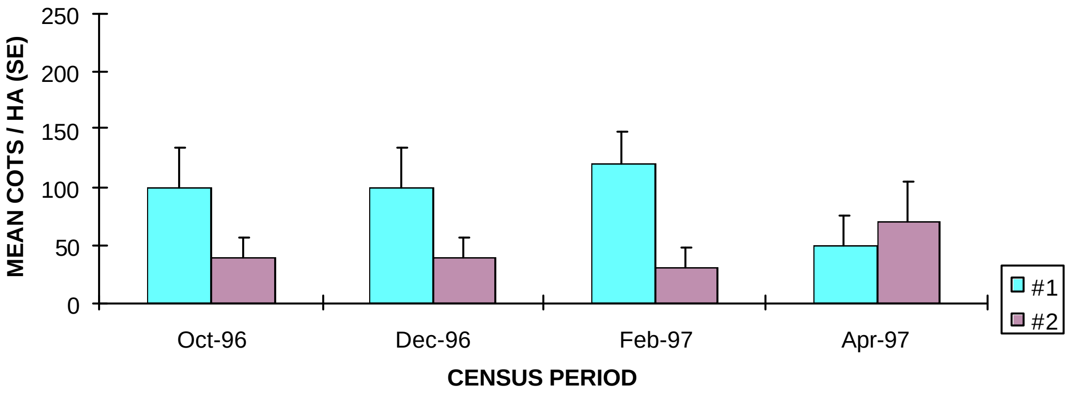
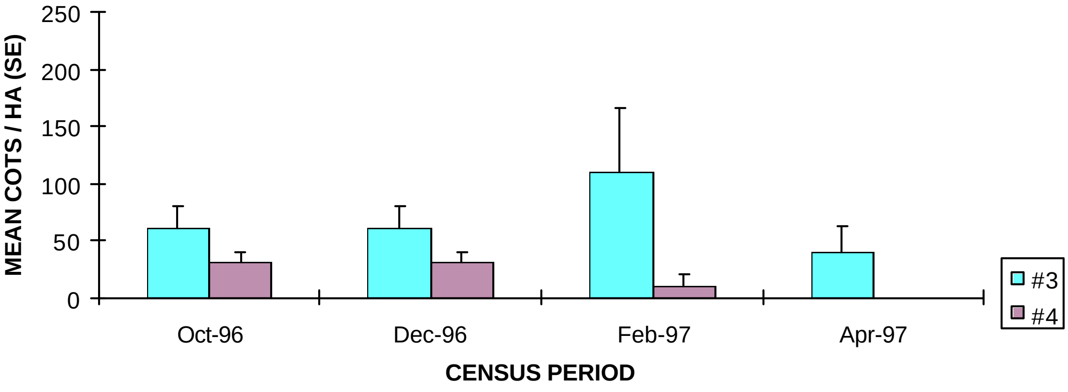


Figure 6. Green Island : The number of COTS injected (top) and effort (COTS / 1 person hour) (bottom) from bimonthly intensive injection visits, where for each visit, injection effort continued for several dives until COTS were no longer found.

WEEKLY TREATMENT



2 MONTHLY TREATMENT



CONTROLS

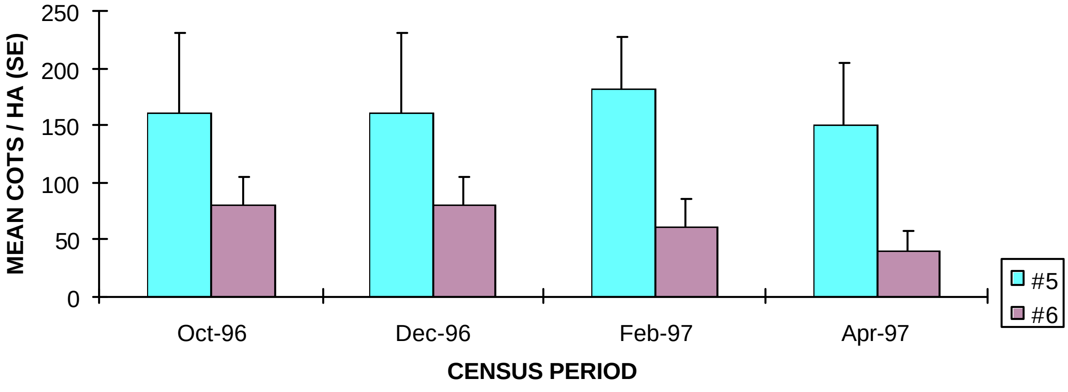


Figure 7. Green Island : COTS densities estimated from belt transects. Densities of COTS were converted to hectares by multiplying the number of COTS counted in each belt by forty. Error bars show standard errors.

Table 1. The five highest ranking taxa recorded with COTS feeding scars at each census and for each of the treatment regimes. *Acropora* spp. are the most highly ranked overall. Total No.Cols. = total number of colonies recorded with recent feeding scars during each census period.

CENSUS	CONTROL	2-MONTHLY	WEEKLY
OCT.1996	*A. formosa*	*A. formosa*	*A. formosa*
	A. nasuta	*A. hyacinthus*	*A. hyacinthus*
	A. tenuis	*A. grandis*	*A. millepora*
	A. millepora	*Montipora enc.*	*A. cerealis*
	A. nobilis	*A. nasuta*	*A. kirsteyi*
Total No.Cols.:	(48)	(181)	(23)
DEC.1996	*A. formosa*	*A. formosa*	*A. hyacinthus*
	A. hyacinthus	*A. hyacinthus*	*A. formosa*
	A. millepora	*A. grandis*	*A. nasuta*
	A. tenuis	*A. elseyi*	*A. elseyi*
	A. elseyi	*A. tenuis*	*A. millepora*
Total No.Cols.:	(113)	(267)	(111)
FEB.1997	*A. formosa*	*A. formosa*	*A. formosa*
	A. hyacinthus	*A. hyacinthus*	*A. hyacinthus*
	A. nobilis	*A. divaricata*	*A. grandis*
	A. nasuta	*A. grandis*	*A. longicyathus*
	A. cytherea	*Montipora* enc	*A. tenuis*
Total No.Cols.:	(59)	(240)	(73)
APR.1997	*A. formosa*	*A. formosa*	*A. formosa*
	A. nobilis	*A. hyacinthus*	*A. hyacinthus*
	A. grandis	*A. nasuta*	*A. nasuta*
	A. hyacinthus	*A. cytherea*	*A. cytherea*
	A. nasuta	*A.divaricata*	*A. grandis*
Total No.Cols.:	(15)	(17)	(33)

COTS Feeding Impacts

A total of 36 species of the 115 species of coral recorded as present in the study area (31% of all species) were found with evidence of COTS feeding scars during the study period. *Acropora* spp. were preferred (scored the highest number of feeding records) by COTS at all sites and at all times during the study, and amongst this genus, *A. formosa* and *A. hyacinthus* were the most preferred species (Table 1).

8. DISCUSSION : GREEN ISLAND

COTS Densities

Differences in COTS densities between designated weekly treatment sites remained unchanged after eight months of substantial eradication effort. However, there were reductions in COTS densities in the 2-monthly sites (#3 and #4), especially in the latter site. It is important to note that COTS densities at the beginning of the study were fifty percent lower at site #4 than at site #3. Therefore, for similar eradication effort at both sites, site #4 was more effectively protected than site #3. This possibly indicates that initial COTS density would influence the relative efficiency of control measures in different locations.

COTS Feeding Preferences

The COTS feeding impact data indicate that most damage occurred with a relatively small number of coral taxa, namely *Acropora* spp., and in particular *A. formosa* and *A. hyacinthus*. These few species were also relatively most abundant and contributed a high proportion of the total live coral cover at all sites. At the same time, individual colonies from most other *Acropora* spp. were also observed with feeding scars. The least affected *Acropora* spp. (in terms of number of records and colony area damaged), were the bushy growth forms such as *A. elseyi* and *A. longicyathus*. This indicates that COTS have a clear order of preference for certain taxa when there is a diverse choice of prey. The COTS in the study sites were probably not in aggregation mode (Moran 1986) as their behaviour was cryptic and feeding was predominantly at night (pers. obs.). In contrast, the larger cohort aggregation observed south of the harbour channel was clearly in aggregation mode. Here, COTS were feeding day and night and most species of coral present were being eaten at the same time (pers. obs.).

9. ACKNOWLEDGMENTS

Thanks to all those who helped with the field work, in particular, the staff of the Lizard Island Research Station. The assistance with statistical methods by two reviewers is greatly appreciated. The COTS tagging study was carried out as a separate project by Lyle Vail and Anne Hoggett and other staff from the Lizard Island Research Station. The results of their work is included here so as all information associated with COTS controls measures is presented in the one document. Special thanks goes to the staff and management of Great Adventures Pty Ltd and Ocean Free Cruises Pty Ltd, for their logistic support and enthusiastic interest and efforts in the Green Island injection program. In particular, I'd like to thank John Percy, Robin Aiello, and the crew of the "Ocean Free" vessel. The comments on the draft version from anonymous reviewers and from Leon Zann, are greatly appreciated.

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11. APPENDICES

Appendix 1. Lizard Island (fixed effects) ANOVA results on percent cover of a range of live and dead coral variables for three treatments and three survey times. The mean square values (MS) are for untransformed % cover data and log (x+1) transformed COTS frequency data. In all cases, the degrees of freedom were as follows: Treatment = 2, Site{Trt} = 3, Survey = 2, Treatment x Survey = 4, Survey*Site{Trt} = 6, Error = 54. P values of the term of interest here (SxT, in bold) which are marked with an * are significant at 0.05 level.

VARIABLE	MS	P	VARIABLE	MS	P
TOTAL HC			*TOT. DEAD CORAL*		
(T)TREATMENT	0.006	0.05	(T)TREATMENT	0.01	0.19
(I)SITE{T}	0.001	0.66	(I)SITE{T}	0.23	0.014
(S)SURVEY	0.046	<0.001	(S)SURVEY	0.03	0.011
S x T	**0.005**	**0.047***	**S x T**	**0.006**	**0.39**
S x I{T}	0.006	0.01	S x I{T}	0.009	0.18
ERROR	0.002		ERROR	0.0001	
MORT. INDEX			*TOT.DEAD ACROP.*		
(T)TREATMENT	0.022	<0.001	(T)TREATMENT	<0.001	0.73
(I)SITE{T}	0.003	0.1	(I)SITE{T}	0.005	0.28
(S)SURVEY	0.025	0.002	(S)SURVEY	0.14	<0.001
S x T	**0.026**	**0.002***	**S x T**	**0.003**	**0.51**
S x I{T}	0.003	0.11	S x I{T}	0.004	0.35
ERROR	0.002		ERROR	0.006	
TOTAL ACROP.			*DEAD TAB.ACROP.*		
(T)TREATMENT	0.09	<0.001	(T)TREATMENT	0.001	0.28
(I)SITE{T}	0.033	<0.001	(I)SITE{T}	0.003	0.05
(S)SURVEY	0.2	<0.001	(S)SURVEY	0.011	<0.001
S x T	**0.009**	**0.92**	**S x T**	**0.003**	**0.022***
S x I{T}	0.009	0.06	S x I{T}	0.001	0.78
ERROR	0.004		ERROR	0.001	
COTS DENSITY					
(T)TREATMENT	0.13	0.18			
(I)SITE{T}	0.12	0.2			
(S)SURVEY	0.25	0.04			
S x T	**0.82**	**<0.001***			
S x I{T}	0.15	0.07			
ERROR	0.075				

Appendix 2. Lizard Island ANOVA results from the control and weekly treatments only for four survey times between October 1995 and August 1996. The mean square values (MS) are for untransformed % cover data and log (x+1) transformed frequency data. In all cases, the degrees of freedom were as follows: Treatment = 1, Site{Trt} = 2, Survey = 3, Treatment x Survey = 3, Survey*Site{Trt} = 6, Error = 48. P values of the term of interest here (TxS, in bold) which are marked with an * are significant at 0.05 level.

VARIABLE	MS	P	VARIABLE	MS	P
TOTAL HC			*TOT. DEAD CORAL*		
(T)TREATMENT	0.018	0.017	(T)TREATMENT	0.003	0.402
(I)SITE{T}	0.004	0.303	(I)SITE{T}	0.03	0.004
(S)SURVEY	0.315	<0.001	(S)SURVEY	0.03	<0.001
S x T	**0.024**	**<0.001***	**S x T**	**0.003**	**0.56**
S x I{T}	0.011	0.003	S x I{T}	0.002	0.85
ERROR	0.003		ERROR	0.005	
MORT. INDEX			*TOT.DEAD ACROP.*		
(T)TREATMENT	0.033	<0.001	(T)TREATMENT	0.003	0.37
(I)SITE{T}	0.003	0.114	(I)SITE{T}	0.012	0.063
(S)SURVEY	0.039	<0.001	(S)SURVEY	0.08	<0.001
S x T	**0.036**	**<0.001***	**S x T**	**0.004**	**0.432**
S x I{T}	0.002	0.08	S x I{T}	0.004	0.49
ERROR	0.001		ERROR	0.004	
TOTAL ACROP.			*DEAD TAB.ACROP.*		
(T)TREATMENT	0.13	<0.001	(T)TREATMENT	0.001	0.96
(I)SITE{T}	0.011	0.16	(I)SITE{T}	0.001	0.18
(S)SURVEY	0.12	<0.001	(S)SURVEY	0.004	0.006
S x T	**0.007**	**0.34**	**S x T**	**0.002**	**0.47**
S x I{T}	0.02	0.02	S x I{T}	0.001	0.42
ERROR	0.006		ERROR	0.001	
COTS DENSITY					
(T)TREATMENT	1.4	<0.001			
(I)SITE{T}	0.004	0.253			
(S)SURVEY	0.17	0.017			
S x T	**1.8**	**<0.001***			
S x I{T}	0.113	0.04			
ERROR	0.045				

Appendix 3. Green Island ANOVA results testing for differences in COTS densities between treatments (2-monthly, weekly, and controls) and census time. Data were lox(x+1) transformed to improve homogeneity following the results of Bartletts test. P values are significant at 0.05 level.

VARIABLE	DF	MS	P
(T)TREATMENT	2	15.8	<0.001
(I)SITE{T}	3	8.62	0.001
(S)SURVEY	3	2.65	0.15
S x T	**6**	**0.46**	**0.93**
S x I{T}	9	1.14	0.78
ERROR	72	1.46	

Appendix 4. The following discussion on implications for management and industry are presented here as an appendix as many of the key issues arising from this study are based on non-scientific information, and hence are considered not appropriate for inclusion in the main text of a technical report. Note, however, that the comments below include scientifically based conclusions contained in this report as well as observations made during the study.

Management Implications

It is possible to reduce COTS densities on small (1-2 ha) patch reefs in the short term but it is not guaranteed to be a lasting situation. Regular or irregular migrations of COTS into a designated area can occur depending on the behaviour and population dynamics of COTS elsewhere on a reef. For practical reasons it is not usually feasible to expand control efforts beyond the area of most concern. However, there can be compelling reasons to be pro-active occasionally and temporarily shift the focus of effort to a COTS aggregations outside the target area, if that area is judged to be under imminent threat from an approaching group of starfish. This will have implications for the policy of restricting control permits to the immediate area of concern. Management therefore should be flexible in their permit conditions to accommodate this situation.

Data on the effects on coral communities of manipulating COTS densities and size classes is not conclusive from this study. More importantly, control measures may not be effective in halting a drop in cover of dominant coral colonies and hence the visual appeal of a site, as migration of COTS (of usually larger individuals) can result in rapid damage to the spatially dominant colonies if they are the preferred species. Clearly, intensive and persistent eradication effort on site, coupled with pre-emptive control measures targeted at COTS in well defined areas beyond the immediate area of concern, would reduce visual impact damage caused by sudden pulses of migrating COTS. Specialist broad-scale assessment of the COTS situation on each reef where control measures are required, is a recommended prerequisite of any control program, and is essential before control activities go beyond the immediate area needing protection.

Industry involvement in this type of work is essential. Observations from industry members who visit sites daily are invaluable and should not be discounted in favour of scientific assessment. While it is acknowledged that it is difficult to maintain scientific rigour in a program involving non-scientifically trained industry members, as has been the case here, this fact does not invalidate such projects. However, this constraint on maintaining scientific rigour should be accommodated in the experimental design and subsequent assessment and review of research findings.

Industry Implications

The protection of a tourism site from significant damage is an essential requirement of any protective program. In terms of visitor satisfaction, the visual appeal of a site is a very important factor to consider. COTS infestations can degrade the visual appeal of a site very rapidly as the larger COTS (in particular) feed preferentially on the large plate and branching corals. The result of this is to replace colourful coral areas with dark unappealing skeletons. It is therefore essential to respond quickly to the presence or to the imminent threat of larger COTS in particular.

This study also demonstrates the importance of regular ongoing control measures. Even when the threat appears to have passed, there is no room for complacency because COTS aggregations show both regular and irregular movements within a reef. It is therefore important to (i) maintain regular inspections of the whole target area, (ii) to continue control measures when COTS numbers are low; and (iii), undertake regular assessments of the status of areas adjacent to the target area, and even of the whole reef, to ensure sufficient warnings can be made for possible remobilisation of staff for control work.

It is also important to note that diver experience, both in terms of general diving experience and in particular COTS eradication experience, could be significant when rapid and effective responses to repeat infestations are required. Therefore, industry managers should be aware that experienced staff are a valuable asset to retain during the possibly 1-2 year history of a current COTS outbreak on a particular reef. To maximise effort, training is required to ensure there is efficient search effort and that locating COTS is effective, particularly when numbers are much lower than in severe outbreak conditions.

There can be a tendency for control personnel to move beyond the immediate lease area so as to sustain high injection returns. This should be discouraged except on the grounds of a specific pro-active move against a perceived imminent threat by an advancing aggregation. This ‘loose cannon’ strategy usually has no real impact on the degree of protection afforded to an important tourism site, and probably only serves to lessen the effect of sustained control measures within the target area.

Appendix 5. Lizard Island data collected during the study which were not presented in the main body of the text. Most of this data did not lend itself to meaningful statistical analysis but was thought to be of sufficient interest to include in the report. Additional details of methodology can be obtained in the equivalent section in the main body of text.

Phase I : Lizard Island

I. COTS Migration and Tagging Study (By L. Vail and A. Hoggett, Lizard Island Research Station)

Methods

A supplementary study (conducted by Lizard Island staff from 24 June to 2 August 1996) involved approximately biweekly injection visits at two of the reefs, and the tagging and following of individual COTS. This study was initiated to investigate whether a very frequent injection regime would be more effective in controlling COTS densities than the initial frequent treatment regime, and whether migration of COTS was occurring into some of the treatment reefs. COTS on a reef adjacent to the two weekly reefs were tagged twice a week during the last 6 weeks of field work. The source reef for tagged COTS contained both control sites (#4, #5) and was about 75 m to 175 m from the treatment sites. Tagging of COTS was done in a zone approximately 15 m wide and 200 m long. This zone extended from the bottom of the reef slope at about 7 m depth, up the slope, and occasionally onto the reef flat. This zone was on the eastern edge of the reef, closest to the treatment reefs. On one occasion, COTS were tagged on a 4-monthly reef (#3) which is about 75 m from reef site #1.

COTS were tagged using numbered squares of coloured flagging tape (approximately 25 mm x 25 mm). Squares of tape were inserted onto at least three dorsal spines of each individual. Only fully exposed individuals were tagged and no attempt was made to tag cryptic individuals. Each tagging session lasted the duration of the dive (usually 60 - 80 min). As many individuals as possible were tagged during this time and individual information recorded on size (maximum diameter, one of four size classes), tag colour and number, and the approximate position of the individual on the reef. For consistency, this information was recorded by the same observer during each visit.

Four approximately evenly spaced underwater markers were placed on the bottom of the reef to assist in describing the position of tagged COTS. In addition, salient landscape features were recorded on a map of the reef and the position of each individual in relation to all of these features was noted. The position of COTS tagged on previous visits was noted and additional tags were applied to individuals with less than three tags remaining.

Results

Location of COTS Found During Injection Activities (June 1996 - August 1996 - Data from Vail and Hoggett, L.I.R.S.)

During June 1996 and August 1996, the position of COTS in relation to the outer perimeter of the two reefs was recorded for 178 and 118 individuals on site #1 and #2, respectively. Most injected COTS were found within 10 m of the outer edge of these reefs with 75% of all COTS at site #1 and 82% at site #2. The percentage injected on the eastern and western sides of the reefs was 39% and 61% for site #1 and 32% and 68% for site #2. These results show that for the latter six week period, most COTS injected on the two reefs were found on the outer western edge of the reefs, especially edges closest to the nearby large reef where the control sites were located.

Tag and Relocation Study (June 1996 - August 1996 - Data from Vail and Hoggett, L.I.R.S.)

Tags were placed on 284 COTS during 14 dives, giving a mean of 20 individuals tagged per dive. Tags remained on individuals for up to 5 days and the greatest loss was due to the shedding of the spine with the tag. The maximum time individuals were followed was for 42 days with 2 individuals being re-tagged 7-8 times during this period. Of the COTS tagged, 3% were 11-20 cm diameter, 79% were 21-40 cm, and 17% were >40 cm, indicating a similar modal size class to the COTS measured on the study reefs (see section above).

Only one tagged COTS moved from the control reef (where it was tagged on 9 July) to an adjacent reef (western side of site #2), where it was found on 13 July. The straight line distance between the tagging location and where it was found was approximately 130 m.

Discussion

It was predicted that the main source of migrants to the weekly treatment sites #1 and #2 was from the large reef to the west. This was inferred from a number of observations including: COTS moving towards the two sites on the inter-reefal sandy patches; by the observed feeding trails on the same two reefs where distinct lines of feeding scars originated from the base edge and progressed into the reef proper (on the side closest to the source reef); and, by the tagging study on COTS migration. The single confirmed movement of a tagged COTS from the predicted source of migrants to the weekly treatment reefs is supplemented by data showing concentrations of injected COTS on the proximal side of these reefs.

II. Injection efficiency

Diver injection efficiency data collected during the study which did not lend itself to statistical treatment and hence is included here as a descriptive result.

Methods

At the end of each field trip, some sites used for injection treatments were re-surveyed to gauge the short term effectiveness of the two injection regimes on COTS densities. Efficiency of the injection treatments was measured in two ways: by diver efficiency in terms of number of COTS killed per unit time, and by the reduction in COTS density at the treatment sites.

Diver experience was measured by categorising the known history of those involved in the weekly injection treatment program. Divers were classified into experienced or inexperienced categories according to whether they were active marine researchers or occasional recreational divers, respectively. The number of COTS injected by divers at the two weekly treatment reefs were pooled for three separate surveys where both experienced and inexperienced divers participated.

Results

Injection Efficiency (October 1995 - June 1996)

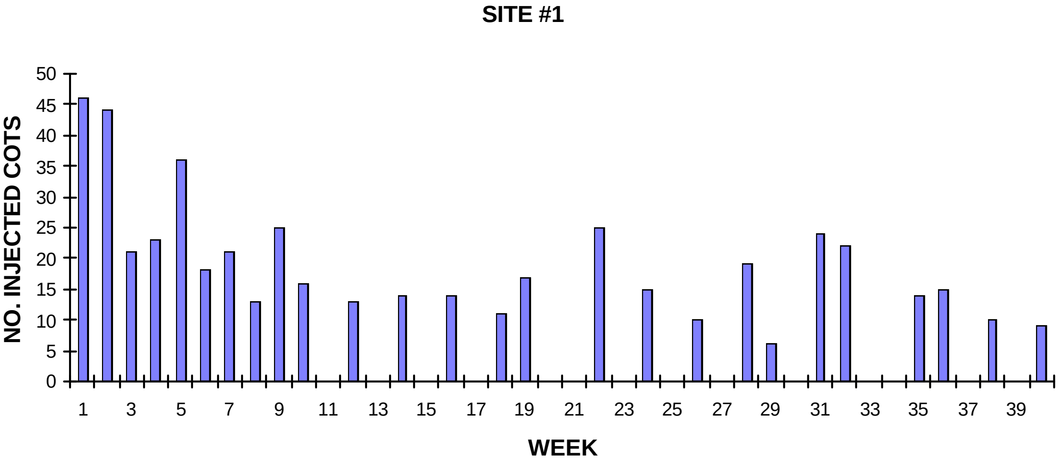
Diver efficiency (ie., number of COTS per person hour) varied between treatments and with time (Table A1). The weekly treatment recorded the highest diver efficiency initially (Table A1), but this was substantially reduced at the two subsequent sampling periods because the initial COTS density was lower, and fewer were found within the time allowed for searching. In contrast, dver efficiency was lower but more consistent under the 4-monthly treatment regime.

The density reduction efficiency increased with time, but at different rates, for both injection treatments (Table A1). The higher number of hours spent in the beginning of the study at the 4-monthly sites had a more immediate impact on COTS densities compared to the effort at the weekly sites. This is seen in the increase in reduction rate at the 4-monthly sites in February, indicating that this injection regime was having an immediate effect on COTS densities. In contrast, the impact on COTS density of the regular weekly injection visits improved more gradually over time. These data suggest that a more efficient strategy for reducing COTS densities at a particular site is to have an initial intensive effort followed by more regular and less intensive visits.

Table A1 Lizard Island injection efficiency, ie. number of COTS per person hour, at the weekly sites (#1,2) and at the 4-monthly sites (#3,6) from October, February, and June. Initial COTS density refers to the belt transect estimates (each belt transect covered 1/40 of a hectare) of density prior to injection treatments. Post injection densities are repeat surveys of the same areas at the end of each injection treatment. The reduction efficiency in COTS densities are calculated from the initial and post injection values.

Treatment	Effort (person hrs)	Diver efficiency (COTS/hour)	Initial density (COTS/ha) (se)	Post-injection density (COTS/ha) (se)	Reduction. Efficiency (%)
Weekly					
Oct 95	4	18	280 (55)	240 (33)	14%
Feb 96	4	10	85 (20)	-	-
Jun 96	4	5	45 (9)	5 (2)	89%
4-Monthly					
Oct 95	14.2	12	360 (39)	85 (19)	54%
Feb 96	11	6	310 (76)	45 (15)	85%
Jun 96	14	8	105 (21)	-	-

The two sites where weekly injection effort was carried out show changes in injection rates due to differences in COTS densities (Figure A1 a, b). That is, at both reefs a decrease in the number of injected COTS was apparent over time with obvious pulses of higher numbers especially when the visit interval lengthened (eg., from one visit each week to one visit every two weeks in the middle twenty weeks, Figure A1 a, b).



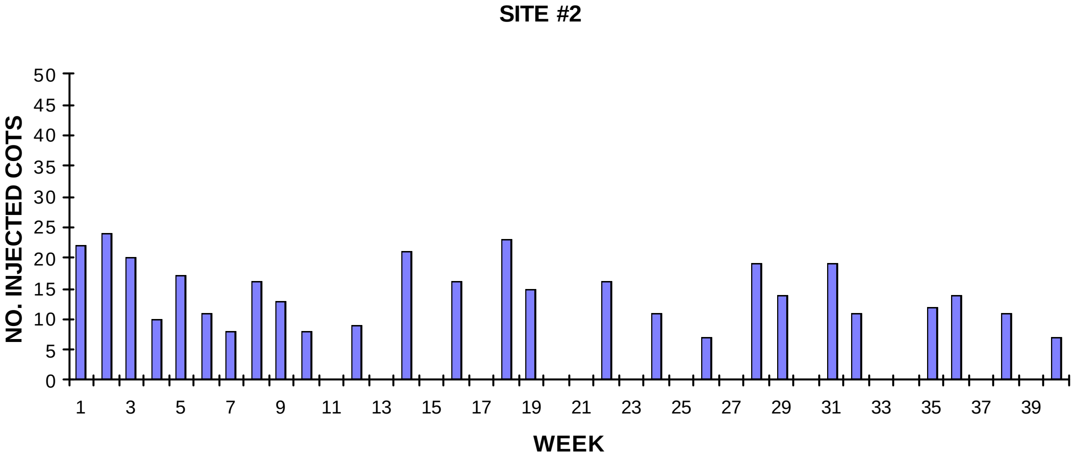


Figure A1(a) Lizard Island : Number of COTS injected per two person hours per visit for the weekly treatment sites between October 1995 and June 1996. There was a visit interval of seven days for the first ten weeks, after which there was an average interval of two weeks. (Figure A1(b) over page)

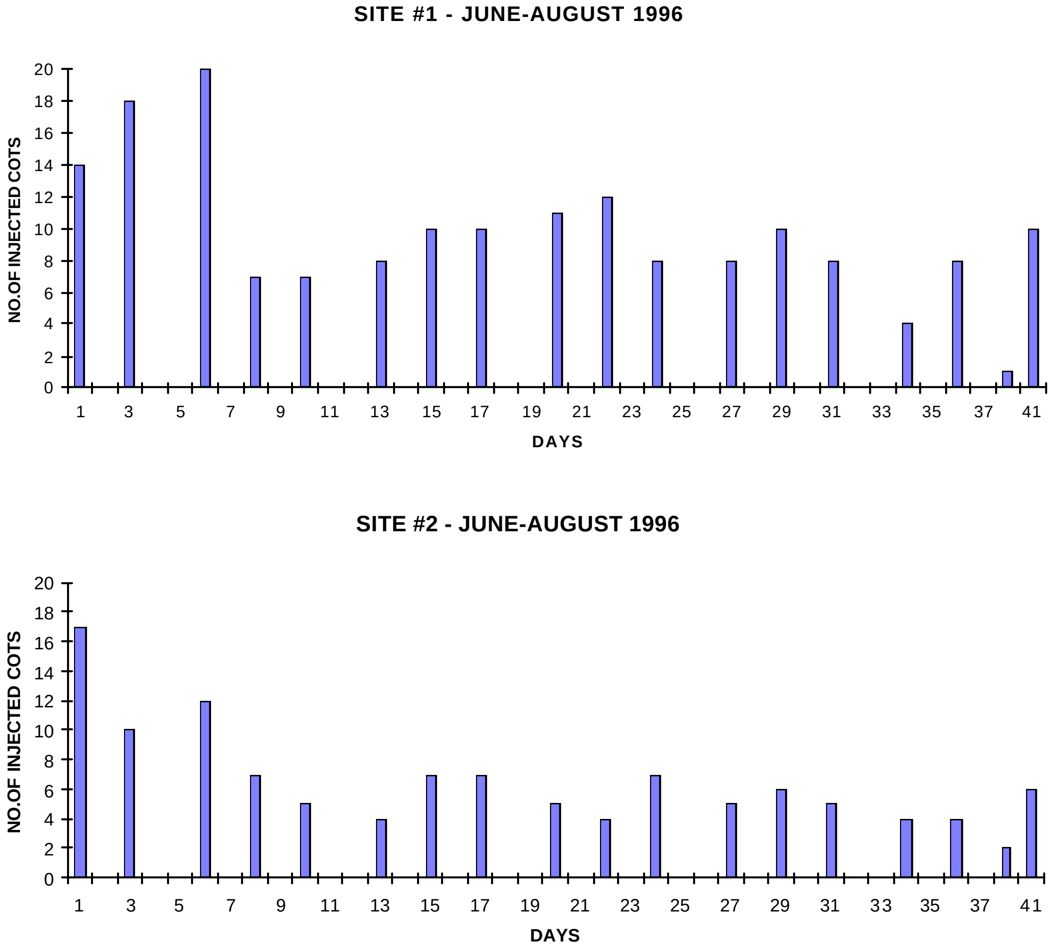


Figure A1(b) Lizard Island : Number of COTS injected per two person hours per visit for the weekly treatment sites from June - August 1996. There was an average visit interval of two days during this period.

Diver Experience

There was a large difference in the ability of experienced and inexperienced divers to find COTS in a specified one hour time period (COTS injection rate of ratio of 4:1, experienced : inexperienced, using data from three visits where the personnel could be clearly designated into either group).

Discussion

Despite the above result and the degree of effort required to significantly lower COTS densities, it appears that coral damage may still occur at these sites. Feeding of large COTS is rapid and damage continued to occur during the intervals between eradication visits. Sporadic migration of COTS into the treated reefs is thought to explain their continued presence at the treatment sites despite the degree of effort shown in this study. Migration into the experimental patch reef sites at Lizard Island meant that COTS had to cross at least several tens of metres of sandy bottom. On larger reefs, migration rates would most likely be higher than the rates experienced in this study because treated and untreated areas would be contiguous and therefore cleared areas would be relatively more accessible to migrating COTS. The most effective interval between visits for a frequent injection regime at both larger reefs and isolated patch reefs is therefore likely to differ. Injection frequency will also change with time, depending upon the stage of the COTS outbreak at which eradication efforts are commenced.

On the 4-monthly treatment sites (with low frequency, high intensity effort) where injections continued until COTS could no longer be found, the cryptic behaviour of COTS ensured that not all individuals were injected. Post-treatment surveys (usually undertaken the following day) confirmed that COTS remained after each intensive eradication visit (Table A1).

Although no wind speed data are available, it was noticed that more COTS were injected at the weekly treatment sites when the weather had been relatively calm for days prior to the visit. This may be due to more individuals adopting exposed positions during calm weather, or to increased migration between reefs during such periods, or both. It is unlikely that the difference was caused by increased diver effectiveness in calm weather because the same area was searched with the same degree of thoroughness under both calm and rough conditions. There is a possibility that diver related search inefficiencies could have been a factor if more inexperienced divers were used in rough weather than in calm weather. This was not the case as at least one experienced diver was always present each injection visit and most new divers participated in injection visits a number of times, so their experience gradually improved over time.

This study has shown that initial diver experience is an important factor affecting the efficiency of control measures. A person experienced in both diving practice and in locating COTS is much more efficient in the injection procedure than an inexperienced person. This is possibly due to that person developing a clear ‘target image’ and a learnt ability to rapidly find a COTS associated with a feeding scar. The target image refers to a diver's ability to instantly locate a small portion of a well-hidden COTS from a background mosaic of very different shapes and colours, usually by observing a small number of spines or part of an arm. Efficient search methods are the key to this learnt ability to find cryptic COTS. Lessons gained from this study have indicated that a diver should search using an oblique observation position, and if necessary, do a circular swimming motion around a feeding scar at a distance of 1-2 m so that the underside of corals and overhangs are surveyed from all possible vantage points.

III. COTS Size Classes

Methods

The maximum diameter was recorded for all COTS encountered during belt transect density estimates and during the weekly and 4-monthly injection visits.

Statistical inferential analysis was not used because COTS size data from belt transects were not of sufficient sample size, whilst size data from the injection records was incomplete (no data are available from the non treatment control sites).

Results

COTS Size Classes (October 1995 - August 1996)

The size-frequency distributions of COTS measured from belt transect surveys showed that all six sites initially had a similar broad spread of size classes (Figure A2). All four injection treatment sites showed a reduction in the overall number of COTS and temporary trends towards a single dominant size class (21-30 cm diameter).

The size class distribution pattern at the weekly treatment sites can be best determined from the injection records (Figure A3). The modal size class was 21-40 cm during most sampling periods, but the mode changed to the 11-20 cm class in some sites as the study progressed.

Size frequency data support the possibility of immigration of 21 to 40 cm diameter individuals into the 4-monthly treatment sites (Figure A2).

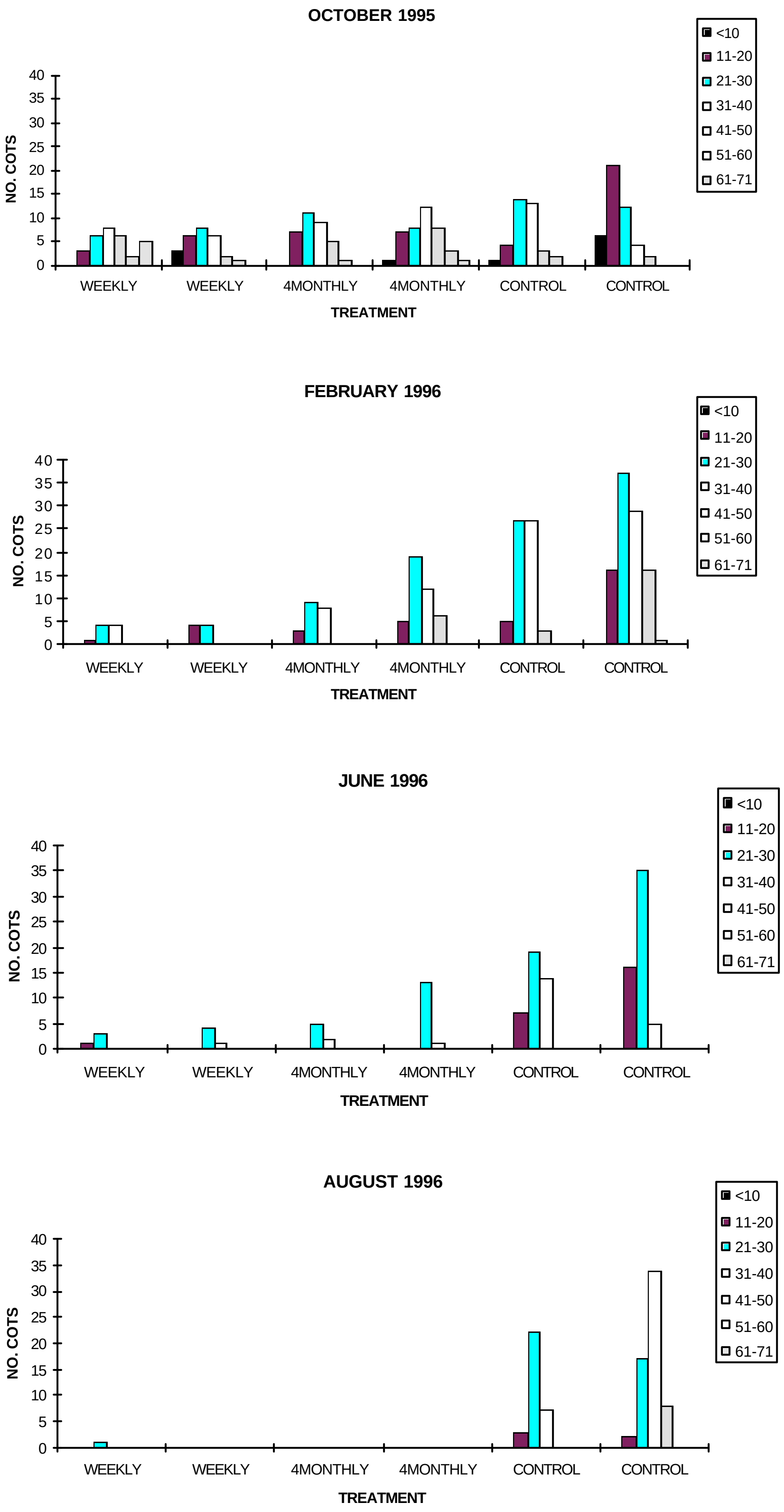


Figure A2. Lizard Island : COTS size classes from all sites and from four survey times. Only COTS density data from the belt transects were used.

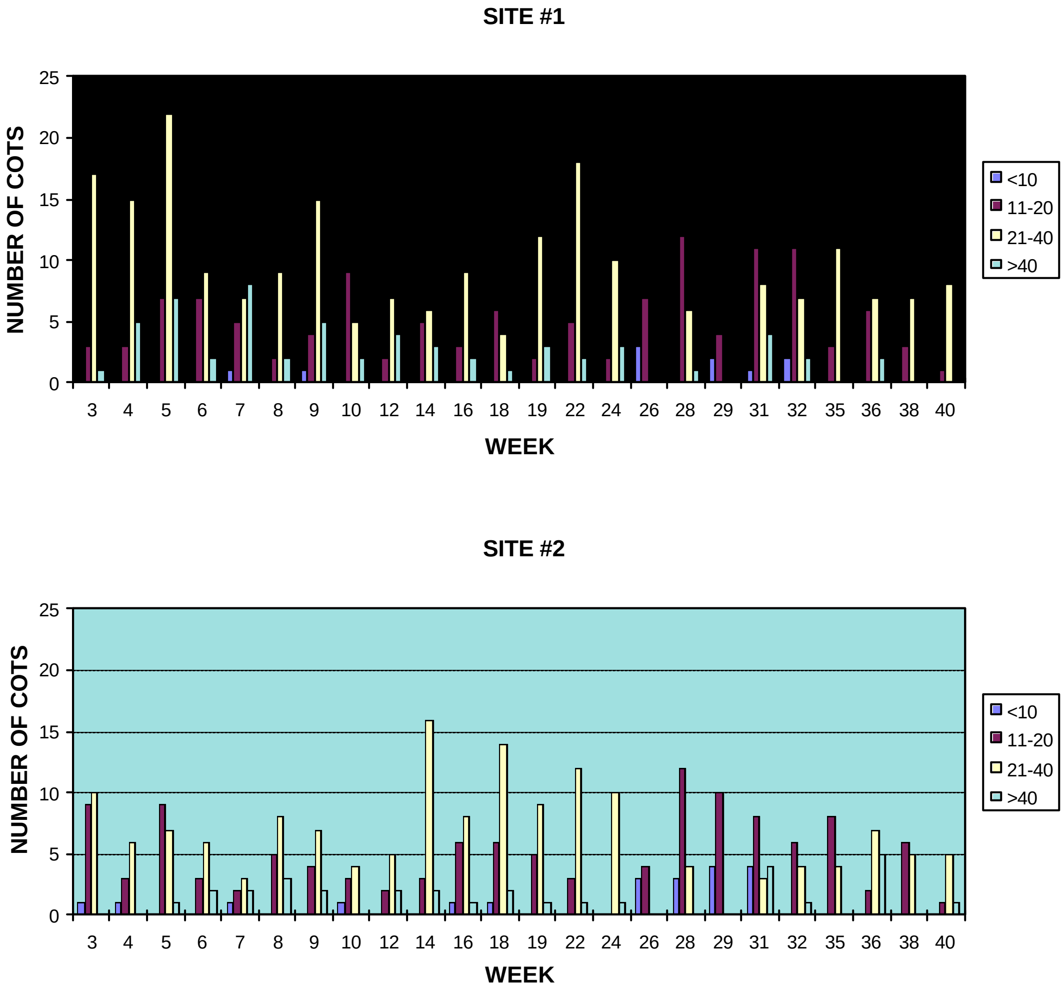


Figure A3. Lizard Island : Size classes of injected COTS from the weekly injection sites (#1,2). Week refer to the number of weeks following the commencement of injection visits in October 1995 to June 1996. The legend shows the 10 cm interval size class categories used here. A shift towards a smaller modal size class can be seen at both sites, which is probably due to the injection treatment.

Discussion

The shifts in modal size class of injected COTS at the four injection treatment sites indicate that this could be a direct effect of the treatments. This effect would be expected given the propensity of divers to more readily locate and inject the larger COTS than the smaller and (usually) more hidden COTS.

IV. Coral Community Data

Methods

Coral species' densities (along with coral fragmentation rates) were collected from eight belt transects using the same tapes set out for the COTS densities and coral cover estimates. Usually the first and last 10 m x 0.3 m wide belts of each of the four tapes were used as sample units. Coral belt results included the number of live coral colonies per unit area, the identification of corals to species where possible (otherwise to genus), and the number of live portions (= number of fragments).

COTS often incompletely feed on large coral colonies, resulting in remnants of live fragments or in a number of remaining smaller colony sizes. Therefore, increases in fragmentation rates and/or reductions in mean colony size were predicted to be a more sensitive index of COTS impact than changes in percent coral cover. Since *Acropora* spp. are particularly favoured by COTS (Moran 1986), the dynamics of this coral genus within a community, with respect to the above indices, is of particular importance, especially since the composition of most coral communities on the GBR are dominated, in terms of percent cover, by this genus.

Results

Mean estimates of coral community indices and COTS densities

The proportion of total hard coral cover contributed by *Acropora* spp. at each site ranged from 50% to 67%. Table A2 shows a difference among treatments sites of total *Acropora* spp. and branching *Acropora* spp. cover. Also, mean *Acropora* spp. cover decreased over time which was due mainly to reductions in cover of branching *Acropora* species.

Table A2. Lizard Island mean cover (and standard errors) of live and dead coral variables and mean COTS densities (and standard errors) sorted into three treatments (means from the first three surveys: October 1995-June 1996) and three survey times (means from three treatments). 4 MO = 4-monthly treatment; TOT HC = combined hard coral; MORT = mortality index; AC TOT = combined *Acropora*; AC CORY = corymbose *Acropora*; AC BR = branching *Acropora*; AC TAB = tabulate *Acropora*; DC TOT = total dead coral; COTS = Crown-of-thorns. August 1996 data were not included here as there is no meaningful comparison between pooled treatments due to the exclusion of the 4-monthly sites for the last survey.

	TREATMENTS			SURVEY TIMES		
VARIABLE	CONTROL	WEEKLY	4MO	OCT.95	FEB.96	JUN.96
% TOT HC	37.9	32.8	37.9	38.6	37.1	32.9
	(2.1)	(1.7)	(1.8)	(2)	(2)	(1.5)
% MORT	0.28	0.29	0.31	0.28	0.33	0.26
	(0.03)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
% AC TOT	27.9	21.1	16.8	25.4	21.5	18.9
	(2.4)	(1.6)	(2.4)	(2.4)	(2.4)	(2.0)
% AC BR	20.6	11.8	10.0	17.4	13.1	11.9
	(2.3)	(1.5)	(1.8)	(2.3)	(2)	(1.9)
% AC TAB	0.9	1.8	1.4	2.0	1.1	1.0
	(0.4)	(0.4)	(0.5)	(0.5)	(0.3)	(0.4)
% DC TOT	15.1	14.1	18.0	16.0	19.1	12.2
	(1.6)	(1.4)	(2.2)	(1.5)	(2.2)	(1.3)
COTS (No.)	545	137	258	351	402	187
	(59)	(20)	(38)	(34)	(76)	(40)

Coral Community Composition (October 1995 - August 1996)

A multi dimensional scaling (MDS) plot showing the relative abundance of corals at each of the treatment sites and between each survey time, is shown in Figure A4. Relative abundance of corals at each survey time is generally very similar to all other survey times within each site. Most sites also show a close affinity in terms of similarity of species' relative abundance. The one exception is at control site #4 where coral composition is clearly different to the other sites. The major difference is because arborescent *Acropora* spp. are relatively more dominant at this site.

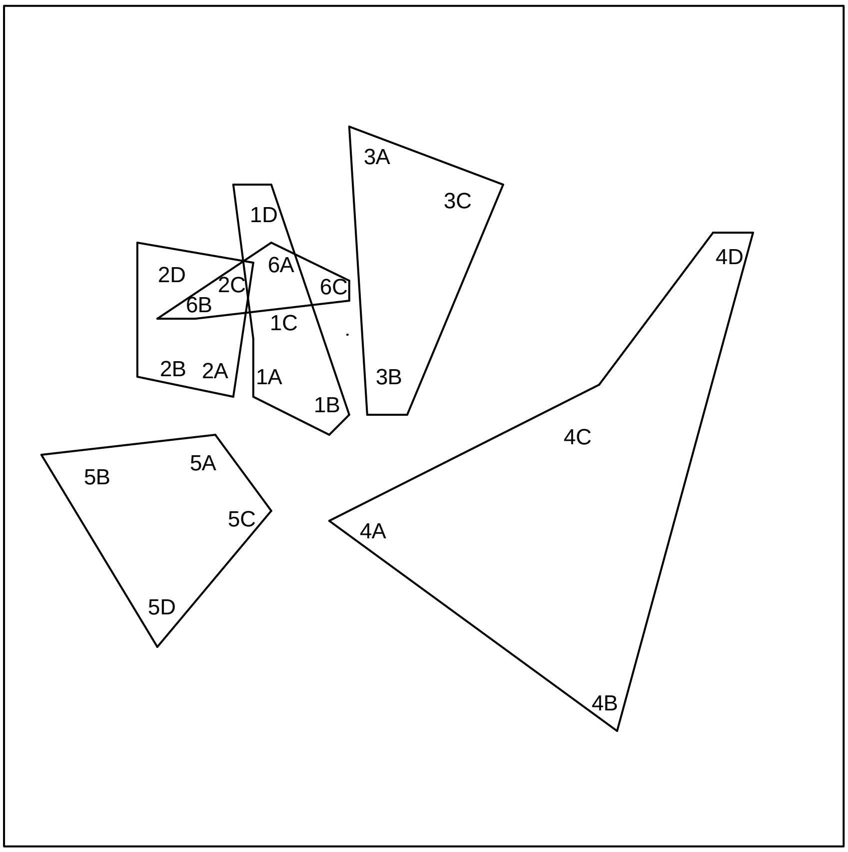


Figure A4. Lizard Island : Multi dimensional scaling (MDS) plot using coral species' relative abundance from each treatment site (surrounded by polygons) and for each survey time (A = October; B = February; C = June; D = August). Site numbers refer to the following treatments : 1,2 = weekly; 3,6 = 4-monthly; 4,5 = no injections. Sites #3 and #6 were not surveyed in August 1996. Stress = 0.2 which means a marginal representation of the relative similarity of each site over time is shown by this plot.

Coral Fragmentation Rates (October 1995 - June 1996)

The rate of colony fragmentation during the first three surveys was low and ranged from 3.2% - 4.2% of all colonies (Table A3). Most occurrences of fragmentation resulted in two daughter colonies, although up to nine daughter colonies were recorded in a small number of arborescent *Acropora* spp. colonies. At all six sites, there was little noticeable change in the frequency of daughter colony numbers in colonies showing fragmentation between October 1995 and June 1996.

Coral Fragmentation Rates (August 1996)

Results from the August survey following the very intensive six week injection program on the weekly treatment sites are inconclusive. Between June and August 1996, there was a two to three times increase in fragmentation rates in both the non treatment control sites and at one of the two weekly sites (Table A3).

Table A3. Lizard Island : Fragmentation rates of coral colonies in each of the six experimental sites. Total = total number of colonies in belt transects. N = the total number of colonies recorded in the belt transects at each site; % Frag = % of colonies with fragments. The 4-monthly treatment sites were not surveyed in August.

	OCTOBER 1995		FEBRUARY 1996		JUNE 1996		AUGUST 1996	
SURVEY	N	% FRAG	N	% FRAG	N	% FRAG	N	% FRAG
WEEKLY	343	4.3	290	2.6	372	3.2	339	6.2
WEEKLY	410	5.0	313	4.6	351	5.1	342	4.7
4-MONTH	333	2.0	283	5.7	433	5.1	-	-
4-MONTH	238	2.1	410	3.0	454	3.1	-	-
CONTROL	355	5.1	179	6.7	224	1.3	218	4.1
CONTROL	443	2.6	234	4.7	221	3.6	205	7.8
TOTAL :	2122	3.2	1709	4.2	2055	3.8	1104	5.6

Discussion

The preferences of COTS to feed on *Acropora* spp. agrees with observations reported elsewhere in the literature (Moran 1986). It was also observed that smaller COTS more commonly feed outwards from the base of arborescent *Acropora* colonies (pers. obs.). This feeding behaviour is relevant to this study and to the indices used to investigate impacts of COTS control measures. COTS generally do not feed on the outer branch tips because of insecure attachment and their relatively higher vulnerability to predation (Birkland and Lucas 1990). The use of coral cover as an index of the status of the coral communities is justified as a measure of visual quality of a reef (an important tourism perspective), but it may not be the best index for the investigation of biological condition or health. The feeding behaviour of COTS and the effect this had on the way live coral cover was measured, meant that there is an inherent delay in COTS feeding effects and significant detection of these impacts. However, other impact indices such as fragmentation rates and changes in relative abundance of coral species were also indicating that for the period of the study no clear pattern of change in coral communities were apparent among the treatment regimes. This is very important to note because it appears that there is a threshold of disturbance at which detection is possible, and this threshold may not have been reached during the period of the study.

The MDS plot showed differences among sites in the degree of changes in species' relative abundance between sample times. Because of these trends, it is difficult to conclude that the situation would remain where there would not be a significant effect on coral cover from the densities of COTS recorded at the study sites. Recent personal communications with Lizard Island Research staff (November 1997) confirm that substantial reductions in coral cover has occurred in both treated and untreated sites during the year following the end of this study. It is possible that the cessation of the study at Lizard Island was premature and that the point where significant differences between treatments would have been detected was not reached during the study period, particularly in the non treatment control sites and in the 4-monthly treatment sites. Alternatively, the impact of COTS aggregations and subsequent changes in species' composition probably occurred prior to the commencement of the study.

Appendix 6. Green Island data collected during the present study which contain non-statistically validated information and conclusions. If required, additional details of methodology may be obtained in the equivalent section in the main body of text.

I. COTS Injection Effort

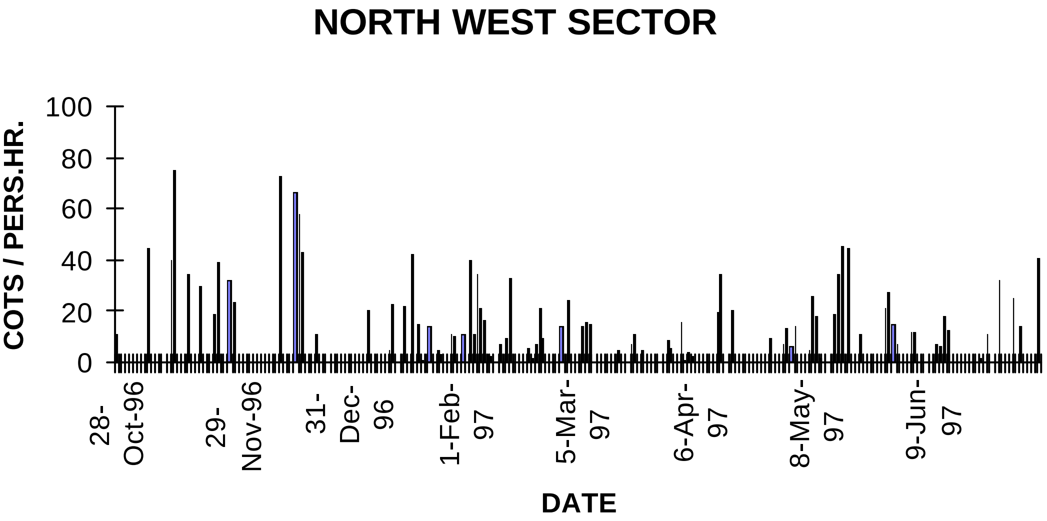
Methods

The methodology has been outlined in the main body of the test in Phase II. Additional COTS information was included from an outer slope site south of the study area because this area was the likely source of COTS migrants into the NW sector, and much of the weekly injection effort in the NW sector was carried out on migrating individuals from this group (pers. obs.; pers.comm. Great Adventures staff).

Results

The weekly injection visits in the NW sector covered an area which included sites #1 and #2, and site #3 (the latter site was treated intensively on a 2-monthly basis as well) and injection records showed pulses of high COTS numbers over time (Figure A5 (top)). This supports the hypothesis that COTS were routinely migrating into this sector from elsewhere.

COTS were also periodically injected outside the designated study area along the outer slope south of the harbour channel (see Figure 5 for location). The injection records from this area showed high injection effort similar to the NW sector (Figure A5).



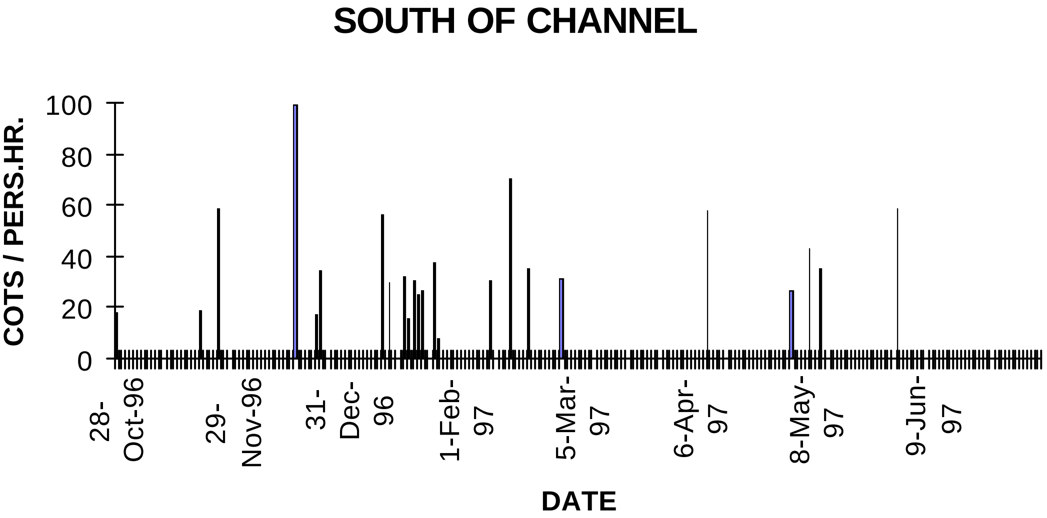


Figure A5. Green Island : Injection effort (number of COTS / person hour) from sites located in the NW sector (top), and at a site south of the harbour channel outside the main study area (bottom).

Discussion

The distinct pulses of high COTS numbers recorded in the weekly injection data over the NW sector indicate that a large pool of COTS were in the vicinity and periodically moved into the area. In contrast, site #4, which is outside the defined NW area, did not appear to be regularly reinfested with COTS. An alternative explanation to the migration hypothesis is that the weekly eradication effort was not sufficiently concentrated to have had any measurable effect on COTS densities in the specific study sites in the NW sector, as weekly visits covered areas adjacent to the study sites as well and migration of COTS into the treatment sites could have occurred from within this sector.

The presence of high numbers of large COTS south of the harbour was an opportune observation arising from the Green Island study. This group was detected at an early stage of invasion of the southern slope, an area which previously contained low COTS numbers. Considerable injection effort was invested in this group (particularly at the northern distribution margin) by the contracted divers undertaking the weekly treatments. Mass invasion and a rapid decrease in coral cover could have also occurred in the NW sector had not considerable effort been used to treat this group in the harbour area and along the deeper outer slope area of the NW sector into which COTS apparently first migrated. Though it is generally not advisable for a control program to go beyond the area of immediate protective concern unless a strategic approach is used, this expansion of effort may have protected some of the most important areas in the NW sector.

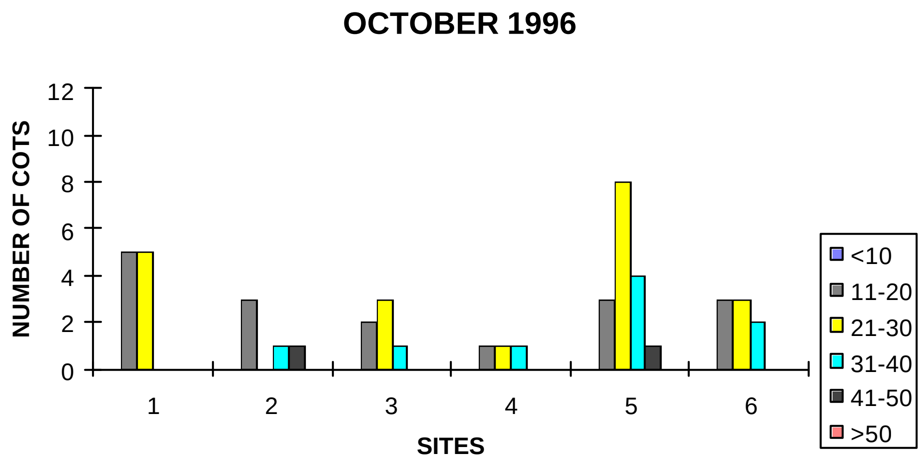
II. COTS Size Classes

Methods

COTS size distributions were investigated by recording the maximum diameters of all COTS encountered during belt transect density estimates and during the 2-monthly injection visits at the two intensively treated sites.

Results

Size class distributions of COTS (from belt transect data) showed little variation over time (Figure A6). The 21-30 cm diameter size class dominated at all sites and at all times, except in December 1996 where the 31-40cm size class dominated in four of the six sites. The sizes of injected COTS at the two 2-monthly sites (#3 and #4, Figure A7 (top and middle)) also showed little change in the dominant size class over time. Size class distribution estimates from injected COTS data are more accurate than estimates based on the belt transect method due to a larger sample size.



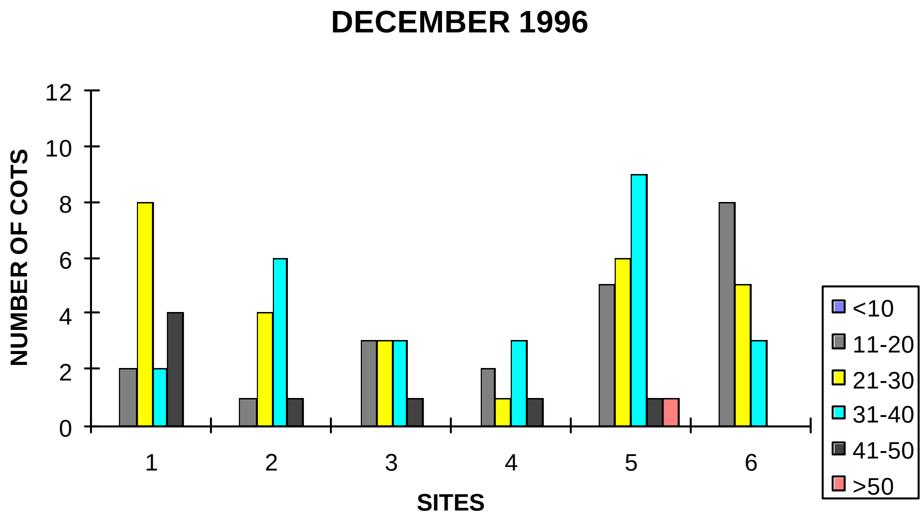
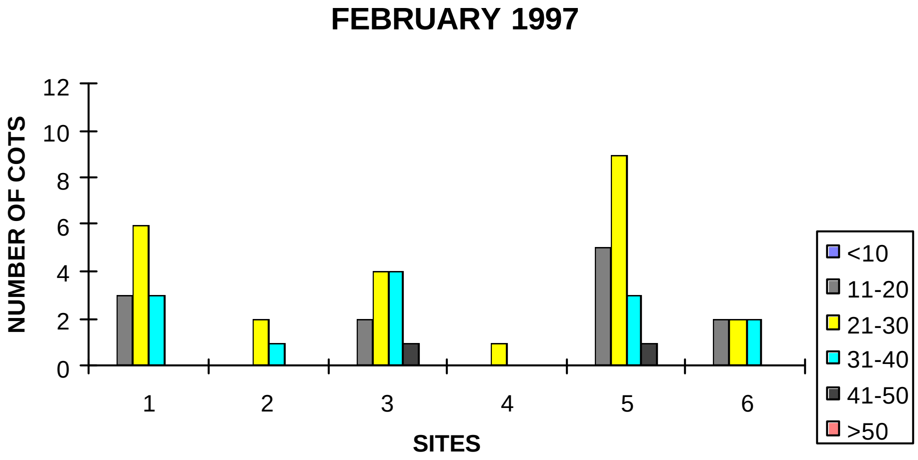


Figure A6. Green Island : Size class distributions of COTS recorded in belt transects from October and December 1996 censuses. (Figure A6 continued over page)



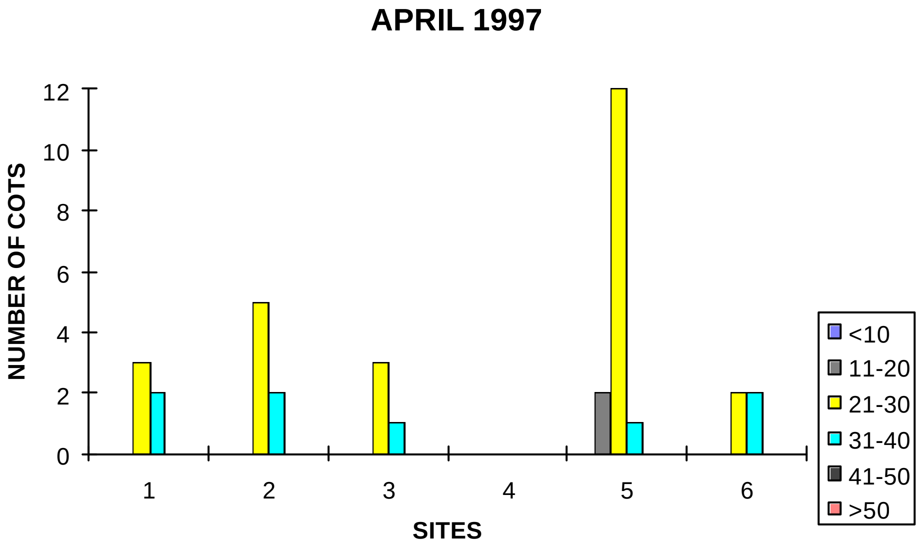


Figure A6 (continued). Green Island : Size class distributions of COTS recorded in belt transects from February and April 1997 censuses.

The size class distribution of a dense mobile aggregation of COTS (recorded in November 1996 at a site south of the harbour channel) consisted of a larger size group of COTS than those encountered in the study area (Figure A7 (bottom)).

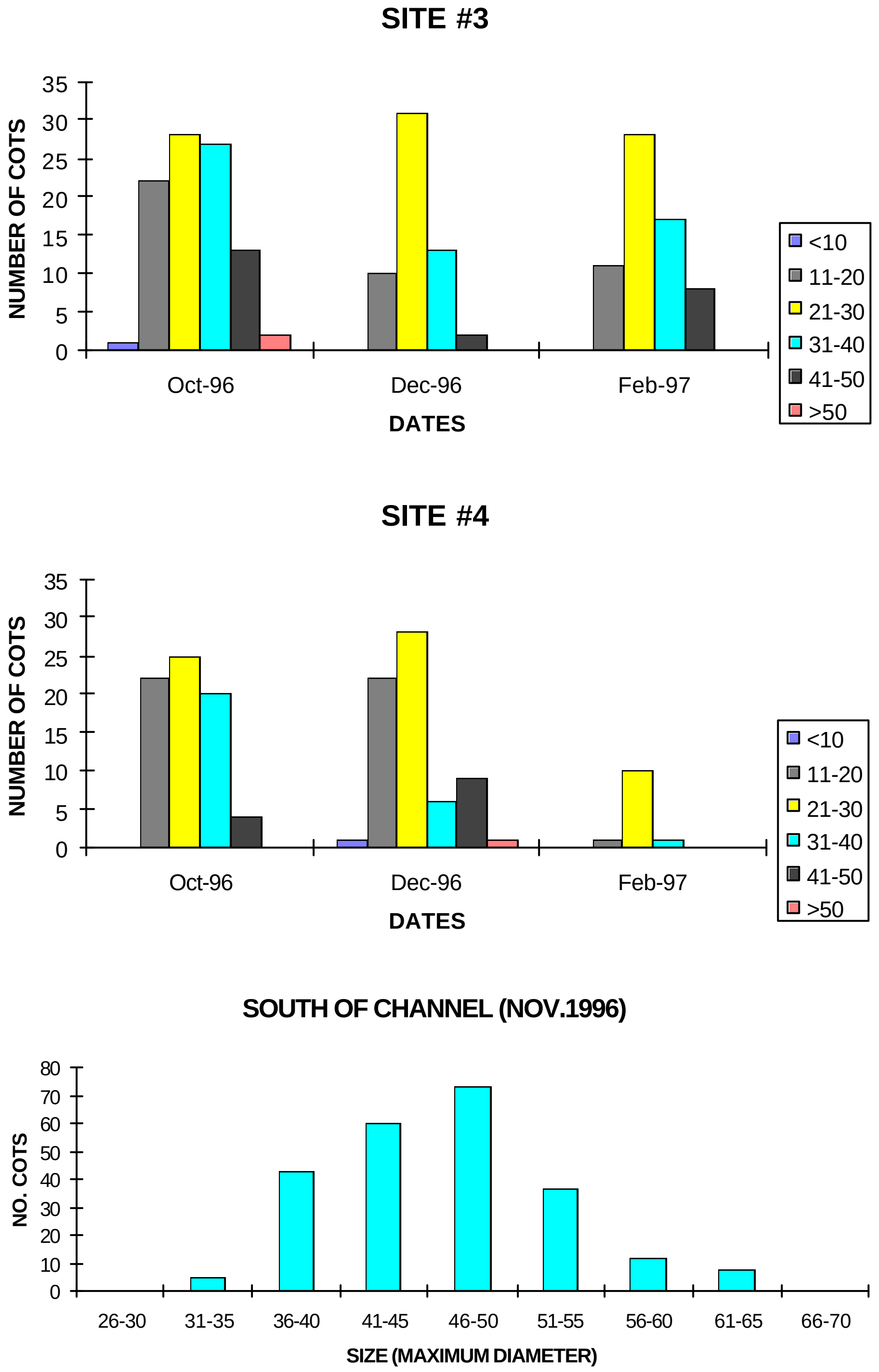


Figure A7. Green Island : COTS size classes recorded from bimonthly treatment injection records at sites #3 and #4 (top, middle). Size classes of COTS measured south of the harbour channel in four 50m x 5m belt transects in November 1996 are shown in the bottom graph. Note that the y-axis in the bottom graph has different size classes showing to the top two graphs.

Discussion

The constant size class structure of COTS over the study period at Green Island (with the exception of the December 1996 survey), is in contrast to the results from Lizard Island, where temporary shifts in size class dominance occurred as a result of eradication effort. The main source of migrants into the NW sector sites at Green Island was a distinctly larger sized COTS group compared to the resident COTS, accounting for the shift to a larger dominant size class in the December survey. The situation was different at the Lizard Island trial reefs, where migrant sizes were similar to the resident COTS and shifts to smaller COTS sizes were found and attributed to the eradication effort.

A number of explanations can account for the relatively constant size class distribution at Green Island : there may have been other sources of migrants in the 21-30 cm size range, thereby maintaining the original size class structure despite injection efforts which tend to selectively reduce the number of larger COTS; the eradication effort may have required a longer period of treatment than the full study period used here to produce a change in size classes; the larger migrant COTS were not advancing into the relatively shallow area where the density surveys were carried out; or, the larger COTS were preferentially killed by the contractors in the deeper outer slope area of the NW sector (prior to COTS moving into the shallower area) where a large portion of the weekly injection effort was carried out, and only the smaller COTS migrated into the study sites. Another explanation for the observed pattern is that the pulses of migrants into the NW study sites did include the larger COTS but this large size group was more effectively eradicated (as was found at Lizard Island). For site #3 (the 2-monthly plus weekly treatment site), this could have resulted in a smaller residual COTS group (dominated by 21-30 cm size individuals) which was then more exhaustively treated during the intensive the 2-monthly eradication visits.

III. Feeding Impacts

Methods

At all sites, detailed records were taken of COTS feeding impacts by focusing on recent feeding scars observed on coral colonies. The feeding impact data are more sensitive indicators of the impact of COTS on coral communities than are the indices of percent coral cover and coral species' relative abundance, because the direct impact on individual colonies is recorded, and not the average impact as in the community indices. At all 2 monthly visits, COTS feeding impact data were recorded. Data were collected by randomly swimming within each of the sites until approximately fifty feeding scars were recorded. Most surveys took from one to two hours per site. Each data record included : the coral growth form present with scars; the maximum diameter of COTS found on or near a scar; the maximum diameter of the colony or colonies showing scars; the percentage of the total area of colonies with recent feeding scars; and the percentage total dead area (which included recent plus older scar area). Both percentage estimates were visually estimated in 20% categories. Areas of colonies were estimated by assuming colonies were approximately circular in outline, and the total area of a colony was calculated by using half the maximum diameter as the colony radius. The impact of COTS feeding was then calculated using total colony area and visual estimates of the percentage area recently eaten, and the percentage area totally dead.

The COTS feeding impact data were used to investigate if changes in feeding impacts occurred as a result of differences in COTS densities. The indices used here included comparisons of : rank abundance of colonies that were recorded with recent feeding scars; the cumulative or net area of impact using the total area of colonies with recent and older eaten portions, the area of immediate colony impact using the area of colonies which had been recently eaten, and the number of colonies recorded with recent feeding scars.

Descriptive comparisons were made on the impact of COTS feeding on major growth forms between treatment sites and survey times. Growth forms included : arborescent *Acropora* spp.; tabulate *Acropora* spp. (*A.hyacinthus*, *A.cytherea*, *A.latistella*); corymbose *Acropora* spp. (all other plate form species,eg, *A.valida*, *A.nasuta*); branching colonies (including bushy *Acropora* spp. (eg, *A.elseyi*); massive; encrusting (eg, *Montipora* spp.); foliose (eg, *Echinopora lamellosa*); and solitary/free living forms (eg, *Fungia* spp.).

Results

The impact of recent COTS feeding behaviour under different injection treatments was qualitatively investigated (Figure A8). The cumulative total dead area of coral in colonies showing recent COTS feeding (Figure A8 (top)) increased over time in the two non-treatment sites (#5, #6) and in a weekly site (#1). In contrast, total dead colony area (from corals with recent feeding scars) remained constant or decreased over time in the two 2-monthly sites

(#3, #4) and one weekly site (#2). The area of recently eaten colonies (Figure A8 (middle)) showed similar but clearer trends described for the total dead area above.

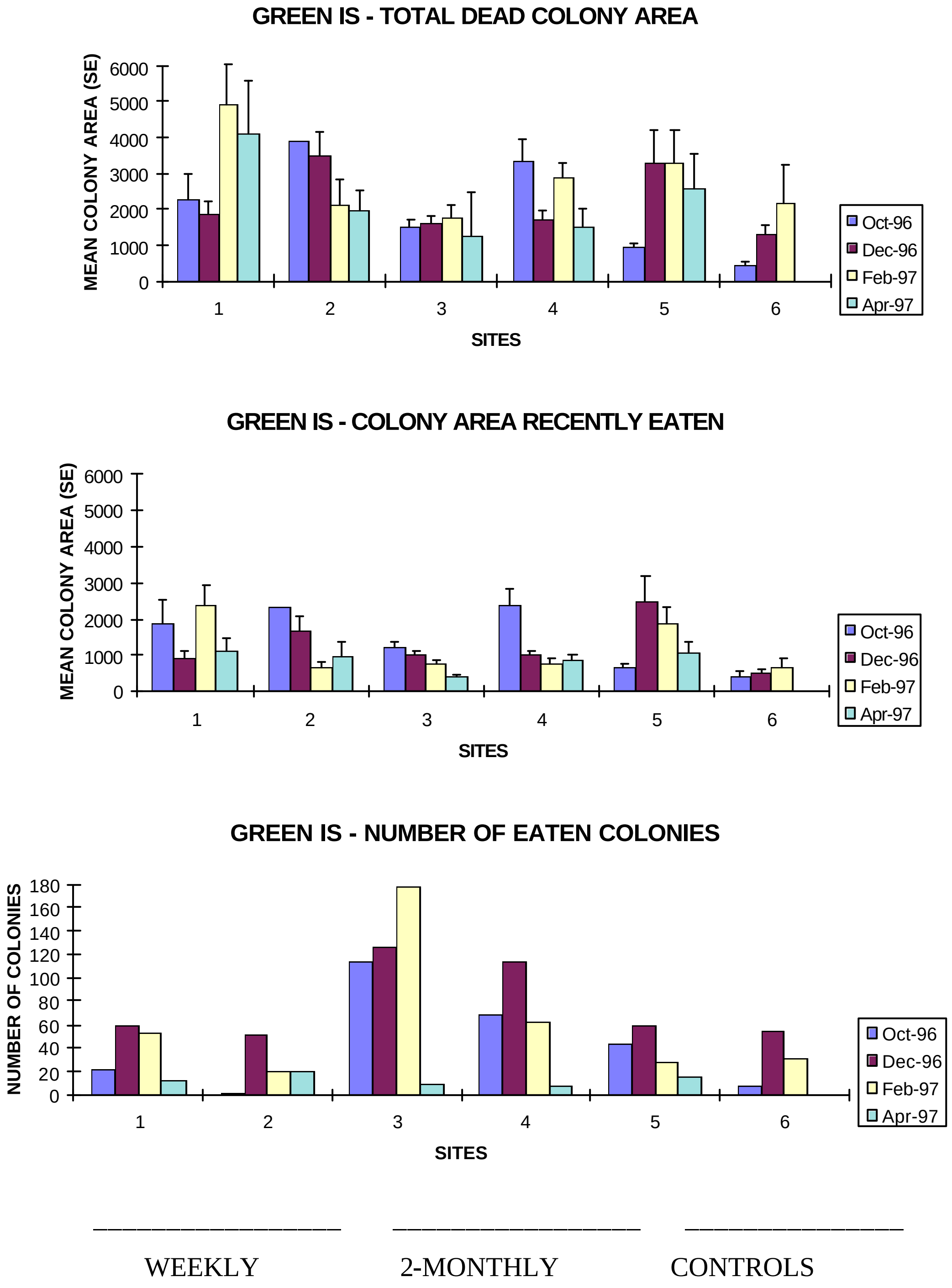


Figure A8. Green Island : COTS feeding impacts comparisons in terms of total dead colony area (top), area of recent feeding (middle), and the number of colonies recorded with recent feeding scars. Area of colonies are in cm^2 and error bars are standard errors. Sites #1 and #2 are weekly treatment sites, sites #3 and #4 are the 2-monthly (plus weekly) treatment sites, and sites #5 and #6 are the non treatment control sites.

The number of colonies found with recent feeding damage during four censuses are shown in Figure A8 (bottom). At some sites, there appears to be an inverse relationship between the number of colonies and the area of impact (or damage) from COTS feeding. This is especially the case when comparing the trends in the two 2-monthly treatment sites (#3, #4) with all the other sites.

Discussion

The feeding impact of COTS on the thirty percent of species which were rare in the study sites may have been more significant in terms of effects on local community diversity. However, the MDS plot (section V below) showed that little change in species' relative abundance occurred among the treatments or during the period from the beginning to the end of the study. Diversity indices based on species' relative abundance therefore would not be expected to have changed during this study. Additional support for this conclusion comes from the observation that most feeding preferences were similar to the rank abundance of species in the local community (see main body of text as well).

However, there were some encouraging trends on the relative effectiveness of the two eradication regimes from the feeding impact data, indicating that this method may be the most sensitive to early changes in community structure. That is, there was an increase in the cumulative and immediate feeding impact in the two non treatment control sites (as well as in one weekly treatment site), at the same time as constant or slightly lower impacts were recorded in the two 2-monthly sites and one weekly site. At the same time, live coral cover (from line intercept transects) in the two 2-monthly treatment sites and one weekly treatment site remained constant over the study period. Assuming from COTS injection data and personal observations of COTS densities outside the study area, that high migration rates were occurring, then this result is indicating that the eradication effort was having a positive result in protecting the coral communities.

It is also possible that the survey method used for feeding impact data was not recording the effects of larger COTS pulses which are evident from the weekly injection records, as it was an instantaneous measure of impact, and these surveys did not necessarily coincide with the high pulse periods. However, increases over time in indices that would detect the impacts from higher COTS pulses (such as dead standing coral cover and the mortality index from line intercept transects), suggest that gradual degradation of the protected sites occurred over the study period. In contrast, the number of colonies found with recent feeding scars was indirectly related to the estimated area being eaten by COTS, suggesting that injection effort is having protective effects in that less coral area was being eaten despite high frequencies of feeding events.

IV. Coral Cover

Methods

Percent coral cover was estimated in the same manner as for the Lizard Island phase using four 30m line intercept transects per site. Coral species' relative abundance and fragmentation rates of corals were also estimated in the same manner as for the Lizard Island phase using eight 10m x 0.3m wide belts per site. In the Lizard Island study, these community indices showed such small changes between 4 monthly visits that it was decided to have longer time intervals between visits. Consequently, percent cover and coral species' relative abundance were only recorded at the beginning and end of the study period only (in October 1996 and April 1997, respectively).

Results

At the beginning and the end of the study period, coral cover was similar in both control sites (#5, #6) but decreased in the weekly treatment sites (#1 and #2), particularly in latter site (Figure A9). During the same time, the mean mortality index increased at both the weekly treatment sites and at one of the two control sites (site #5, Figure A10, Table A4). The COTS injection effort therefore did not appear to prevent an increase in the mortality index during the study period.

Figure A11 shows live coral cover of the major growth forms for each of the sites at the beginning and the end of the study. In all but one site (non treatment control site #6), cover of tabulate *Acropora* spp. had decreased by the end of the study. Cover of the other major growth forms remained approximately the same.

Table A4. Green Island coral cover and COTS densities (standard errors in brackets). TOT.HC = total hard coral; MORT.IND = index of mortality; TOT.AC = total *Acropora* spp.; CORY.AC = corymbose *Acropora* spp.; ARB.AC = arborescent *Acropora* spp.; TAB.AC = tabulate *Acropora* spp.; DC.HC = total dead hard coral; COTS = crown-of-thorns density from belt transects.

	TREATMENTS			SURVEY TIMES	
FORM	CONTROLS	WEEKLY	2-MONTH	OCT.1996	APR.1997
TOT.HC	65.5 (1.1)	58.0 (4.5)	52.8 (1.7)	61.1 (2.9)	56.4 (3.2)
MORT.IND.	0.2 (0.04)	0.25 (0.07)	0.33 (0.03)	0.19 (0.08)	0.33 (0.09)
TOT.AC.	62.3 (1.2)	54.0 (4.3)	47.0 (3.0)	57.5 (3.3)	51.3 (3.6)
CORY.AC.	12.7 (2.1)	5.0 (2.0)	7.7 (3.0)	9.3 (2.1)	7.6 (1.1)
ARBOR.AC	34.1 (2.7)	30.5 (1.9)	26.4 (3.4)	32.1 (1.9)	28.6 (2.9)
TAB.AC	6.8 (3.1)	7.6 (1.9)	5.5 (1.0)	7.1 (1.9)	6.1 (1.6)
TOT.DC	12.5 (2.6)	12.6 (2.7)	16.8 (1.6)	10.6 (1.3)	17.3 (1.5)
COTS	28.4 (4.2)	17.2 (2.5)	10.6 (2.4)	19.6 (3.9)	15.0 (3.7)

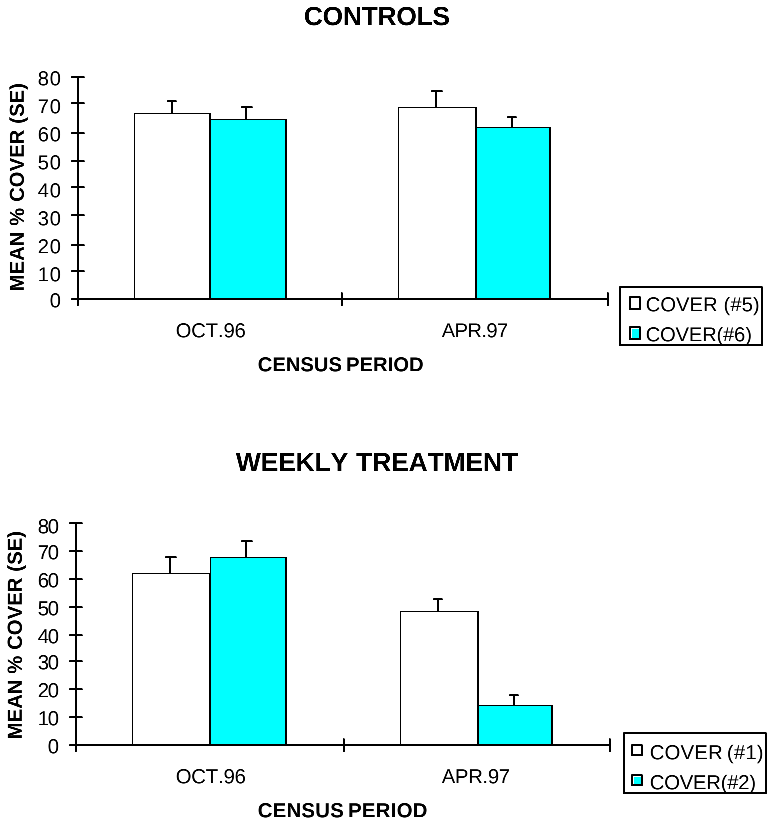


Figure A9. Green Island : Mean live coral cover at the non treatment control sites and the weekly treatment sites, at the beginning (October 1996) and the end (April 1997) of the study.

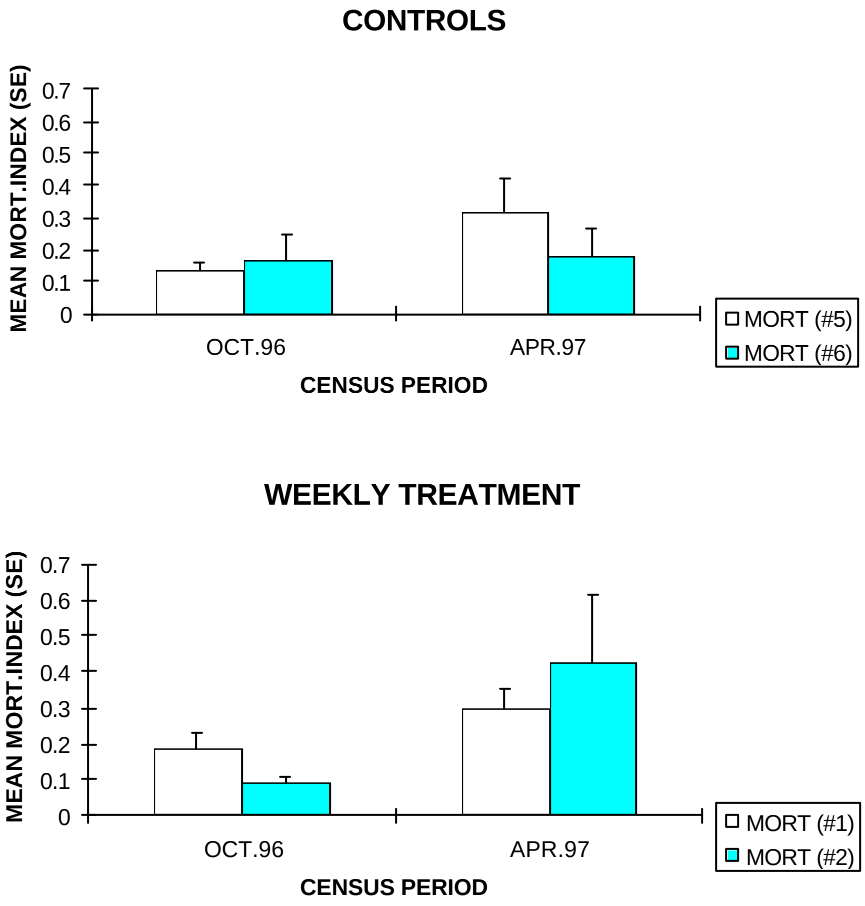


Figure A10. Green Island : Mean mortality indices from non treatment control sites (#5, #6) and weekly treatment (#1, #2) at the beginning (October 1996) and the end (April 1997) of the study period.

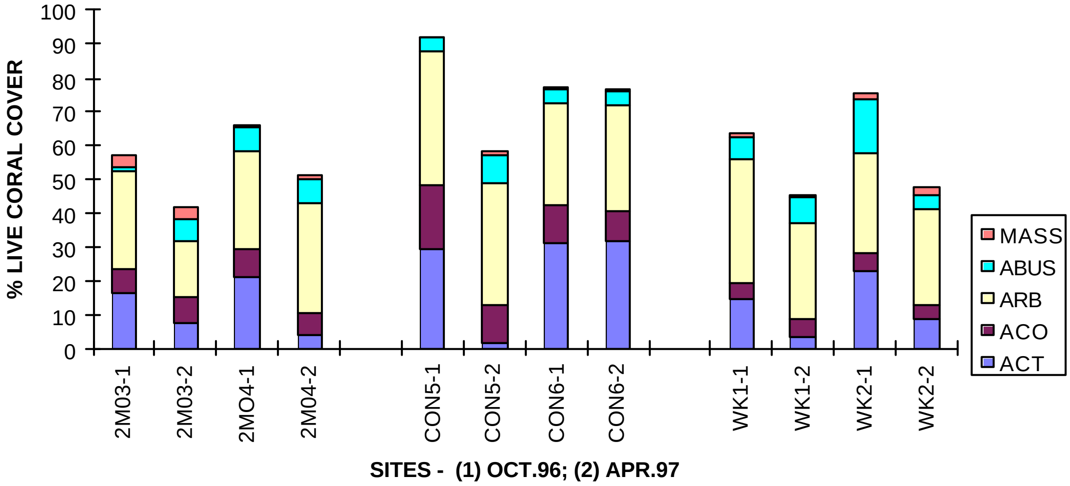


Figure A11. Green Island : Live coral cover of major growth forms for each site at the beginning (October 1996 = (1), and the end April 1997 (2) of the study. Data are arranged into treatment groups. MASS = massive forms; ABUS = bushy *Acropora* spp; ARB = arborescent *Acropora* spp.; ACO = corymbose *Acropora* spp.; ACT == tabulate *Acropora* spp.; 2MO, CON, and WK refer to the three treatments assigned to sites. For example, 2MO3-1 refers to growth form cover at the 2 monthly treatment site #3 in October 1996.

Discussion

The lack of change in live coral cover in the control sites may have been due to the maximum summer growth of dominant fast growing *Acropora* species. Since tabulate *Acropora* spp. showed a decrease in cover irrespective of treatment regime, and since no noticeable change in cover occurred in most other major growth forms, then growth would have occurred primarily in the other main fast growing species, the arborescent *Acropora* species. This is supported by trends in arborescent *Acropora* spp. cover which remained more or less constant over the study period at all sites, despite feeding preference data indicating that this growth form was highly favoured by COTS. Alternatively, the line intercept methodology may not be sufficiently accurate to detect changes in live coral cover except for gross changes. This point has also been raised in the Lizard Island study phase.

In contrast, there was a predictable clear relationship between live coral cover and the mortality index. Here, as live cover decreased between the beginning and the end of the study, a corresponding increase in the mortality index was also detected. The result also indicates that the injection regime was apparently not having an effect on the protection of coral cover. Also, it is clear from these data that the experiment did not progress as was expected, vindicating the conclusion that formal statistical analyses of this phase of the data was not warranted.

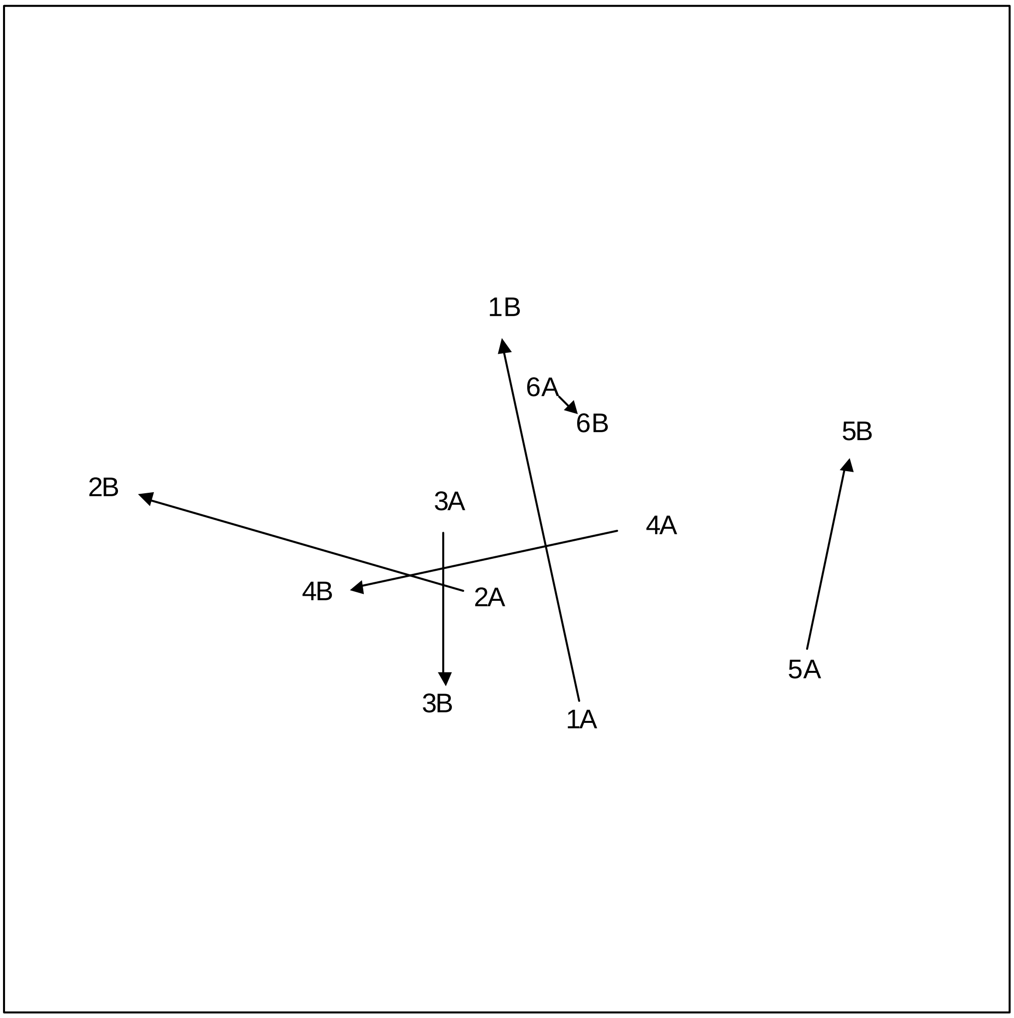


Figure A12. Green Island : MDS plot of relative coral abundance estimated from belt transects at the beginning (October 1996) and the end of the study (April 1997). Site identification numbers data are labelled with the suffix (A) or (B) indicating October 1996 and April 1997 data, respectively. The most dissimilar sites and sample times within sites with respect to species' relative abundance, are more spatially separated. Stress = 0.15.

V. Community Composition and Relative Abundance

Methods

Species' relative abundance and fragmentation rates were recorded from 8 x 10m x 0.3m wide belt transects per site. Two belt transects were used from each of four transect lines. Data were recorded and analysed in the same manner as in the Lizard Island phase I. A non-metric multidimensional scaling technique (MDS) was used to investigate changes in species' relative abundance. As well, fragmentation rates were noted during the recording of species' relative abundance.

Results

Changes in Community Composition

The similarity of sites with respect to the relative abundance of coral taxa (recorded in belt transects) are shown in an MDS plot (Figure A12). Some sites showed relatively large changes in their position in the MDS plot (relative to other sites, and relative to their species' composition at the beginning and end of the study) indicating similarly large changes in relative abundance. For example, all sites except site #5 were relatively similar in species' relative abundance at the beginning of the study but were less similar to each other at the end of the study. Sites #1 and #2 showed the greatest changes in species' relative abundance between the beginning and end of the study.

Coral Fragmentation

Fragmentation rates (used here as an index of COTS impacts, due to their tendency to incompletely eat all colonies) were low at the beginning and end of the study, ranging from 0.95% to 3.45% of all colonies in the belt transects (Table A5). Most fragmentation resulted in two daughter colonies (61% of all fragmented colonies in October 1996, and 76% in April 1997). *Acropora* spp. had the highest proportion of colonies with fragments (79% and 60% of all fragmented colonies in October 1996 and April 1997, respectively). Arborescent, corymbose, and tabulate *Acropora* spp. had similar fragmentation rates in October 1996, but arborescent forms had higher rates in April 1997 (23% of all fragmented *Acropora* spp. colonies in October 1996 to 47% in April 1996).

Pooled remnant colonies from all sites increased from a total of 31 in October to 53 in April (Table A5). Site #3 showed a reduction in the percentage of remnants during the study period in contrast to the other 2-monthly treatment site #4 which had similar numbers of remnants.

The weekly sites and non treatment control sites showed only small reductions in the frequency of remnants.

Table A5. Green Island : Percentage fragmentation and remnants recorded from belt transects. N = total number of colonies ; FRAG = percent colonies with fragmentation; REMN.= percentage of colonies as remnants.

	OCTOBER 1996			APRIL 1997		
	N	FRAG (%)	REMN. (%)	N	FRAG (%)	REMN. (%)
2-MONTHLY (#3)	305	2.6	5.3	220	2.3	0.5
2-MONTHLY (#4)	243	1.23	6.2	187	3.2	7.5
CONTROL (#5)	210	0.95	2.9	174	3.5	2.3
CONTROL (#6)	272	2.6	1.8	243	2.5	1.2
WEEKLY (#1)	213	1.4	2.8	182	1.1	1.1
WEEKLY (#2)	292	1.7	3.4	253	2.4	2.4

Discussion

Species' Relative Abundance

The MDS plot indicates that some sites had experienced relatively large changes in relative species' composition during the period of the study. Two of the three sites in the NW sector (#1, #2) which were closest to the western edge of the reef (where the high numbers of COTS were observed and injected) showed relatively large changes in relative abundance. These two sites also suffered major impacts from cyclone "Justin" so the degree of impact from the two sources of disturbance cannot be determined. Sites #3 and #4 were expected to be the most intensively protected, and relatively small change in composition in site #3 appears to support this expectation. Site #4 was indicating relatively greater change but this site also was significantly damaged by the same cyclone.

Fragmentation Rates

Fragmentation rates and frequencies of remnants may be more sensitive indices of early-stage impacts than changes in coral cover because of the manner in which COTS feed on corals when in non aggregation mode. Feeding by COTS in non aggregation mode is usually incomplete (especially on arborescent *Acropora* spp.) and live portions of colonies remain for some time after single feeding events (pers. obs.). It appears that in non aggregation situations, COTS will gradually devour a large coral colony over a number of days, usually by resting during daylight hours near the colony in a cryptic position, and resuming feeding on the colony at night (pers. obs.). Therefore, although low fragmentation and remnant frequencies were recorded at all sites, small increases in these frequencies can be indicative of low level impacts occurring to the community as a whole. For example, fragmentation rates were highest in *Acropora* spp. which are the main prey of COTS.

The observed increase in the frequency of fragmentation in at least one site from each of the three treatment regimes indicates that COTS were having an impact to some extent in all areas. In contrast, lower frequencies of remnants observed in some of the weekly and 2-monthly sites suggest that eradication efforts could be reducing the impact of COTS activities. Alternatively, the eradication efforts could have been the cause of an increase in the incidence of fragmentation by increasing the number of incomplete feeding events on individual colonies. This is because COTS are most likely to be detected and killed when consumption of colonies is occurring. In fact, the detection of cryptic COTS is usually enhanced by the presence of recent feeding scars on corals. However, increases in fragmentation rates due to eradication efforts was not obvious from the Green Island study as similar trends in fragmentation rates are seen in the non treatment sites.

Appendix 7. Observations and anecdotal information on COTS behaviour and other relevant coral and reef information obtained during the period of the study. This information is not scientifically substantiated but nonetheless it may be important in terms of effective COTS control measures. Observations are from both phases of the study and are referred to one of the two reef locations if observations are specific to that phase.

(a) COTS Behaviour

- The characteristics of a COTS outbreak can differ in two ways, which will have implications for the type of eradication strategy to adopt : there can be differences in replacement rates of COTS, and there can be differences in feeding preferences depending on whether an outbreak is at an early or late stage of an outbreak.

- Smaller COTS (<20-25 cm diameter) are often less selective in their choice of coral prey species than larger COTS. Small COTS remain in the more cryptic protected parts of a patch reef (especially during the day) and feed on all corals, including small (possibly recruit) colonies, and on slower growing colonies that are less preferred by adult COTS in non-aggregation mode.

- Lizard Island and Green Island COTS migration rates were probably different to each other though at both, the rates appeared to be sufficient to offset the reduction in COTS from injection treatments.

- Other COTS-related variables not tested in this study should also be considered, including the size of nearby populations, the proximity of migrating COTS, and recent weather conditions. Additional input into the population from new recruits also needs to be addressed, perhaps with an additional intensive treatment each year at the stage when young COTS start to actively feed on corals.

- Migrating COTS can appear in sudden pulses, rapidly invading a site within a day.

- At Green Island, it appears that a large COTS cohort came out of deep water possibly originating from further to the south along the outer slope (pers. obs.). The complete denudation of most live coral in this high aggregation area occurred within a month of the first appearance of COTS (pers. obs.). I estimated that an area of slope south of the harbour entrance and up to one km in length was affected at the same time.

- This south channel COTS group is believed to be the source of the high COTS pulses recorded in the weekly injection records from the NW sector study area. This conclusion is based on two factors : (i) much of the injection effort (and high COTS injection records) was concentrated on the deeper (av.10 m depth) outer slope areas along the NW sector; and (ii), numerous observations were made of COTS moving northwards across the channel entrance in deeper water (J. Percy, pers. obs.).

- COTS tend to move into and out of shallow water depths, possibly as a result of wind and/or water turbulence levels.

- There can be differences in COTS feeding preferences depending on the stage of an outbreak and on the size class distribution of the COTS.

?? Due to the mode of COTS feeding, it was expected that that there would be a delayed signal on the impact of COTS on the estimates of coral cover from line intercept methods. This is because COTS tend to feed from the base outwards in branching colonies (especially *Acropora* spp.) and from the under side to the upper side of plate *Acropora* spp.(pers. obs.). For this reason, coral belt transect data, including colony size, number of fragments, and remnant colonies, were recorded at the same time.

(b) Injection Regimes

?? It is obvious from this study that the smaller COTS were hard to eliminate from an area and required a good deal of search effort to find, resulting in the short term in a relatively greater reduction of larger individuals compared to smaller individuals.

?? The additional increased diver orientation afforded by the presence of transect line(s) or tapes/ropes, clearly allows better detection of cryptic COTS per unit time than searches made by haphazardly-swimming divers.

?? To maximise the effectiveness of a control program, training and on site experience of divers is essential.

?? The initial COTS density at a site will influence the ability of control measures to reduce COTS numbers in the short term.

?? Regular ongoing visits should be maintained in the target area even when there is a noticeable drop in COTS numbers.

?? A control program has to be in place for the duration of an outbreak on a reef (1-2 years) and needs to be flexible and have the ability at short notice to change the area of focus of control effort, and to change the intensity of effort.

?? Migration characteristics from adjacent areas will dictate the type and amount of control effort used to control COTS numbers. As part of this factor, it is essential to have knowledge of the COTS situation beyond the boundaries of the target area.

?? Treatment of COTS in areas off site should be approached in a strategic manner if there is potential for migration into the target site requiring protection. Unplanned “off site” eradication effort may have helped in stemming the degree of damage in the study sites at Green Island. This was concluded from the observations on the movements of COTS in the “off site” south channel area, and from the extreme damage to corals there.

?? No single strategy will be applicable in all situations. Both intensity of effort and the interval between visits should be determined on a case by case basis. The rate of COTS replacement is the critical factor to take into account when determining the appropriate eradication regime for a protective program.

?? A combination of initial intensive eradication events, each of which continue until close to zero injection rates are reached within an average dive time, with regular eradication (2 person hours/week) appear to be the most effective regime under the circumstances encountered during this study.

(c) Coral Community Impacts

?? Coral community structure may still be impacted at a site where effective COTS eradication is occurring, but the effects will be much slower than in the absence of eradication efforts. Impacts tend to be predominantly on the smaller, less abundant and more cryptic species, possibly reducing the diversity of a site but not the visual appeal. Less effective eradication efforts may slow down the deterioration of a site but probably will not be effective in avoiding noticeable visual damage to the spatially dominant and generally more preferred prey species in the long term. The latter situation can occur rapidly if there are large COTS (>40cm dia) in a site, or if high numbers of large individuals are migrating into a protected site from adjacent areas.

(d) Cyclone Impacts

?? The impact of cyclone “Justin” (1997) on coral colonies on Green Island may have contributed significantly to an increase in the coral mortality indices at the two weekly treatment sites (#1, #2) and at the control site #5. Damage from cyclones include overturning of colonies (especially branching colonies) which are usually dead on the lower base areas. This exposes more of the dead colony surface area and leads to a higher estimate of the mortality index.