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C.P. Catterall

Griffith University, Division of Australian Environmental Studies, Nathan Queensland 4111

I.R. Poiner

CSIRO Division of Fisheries, CSIRO Marine Laboratories, PO Box 120, Cleveland Queensland 4163

J. Kerr

CSIRO Division of Mathematics and Statistics, CSIRO Long Pocket Laboratories, Private Bag No. 3, Indooroopilly Queensland 4068

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Great Barrier Reef Marine Park Authority

PO Box 1379
Townsville Qld 4810
Telephone (077) 818811

Impact of dredging on the volute Cymbiolacca pulchra and its environment at Heron Island, Great Barrier Reef, Australia.

C. P. Catterall[1], I.R. Poiner[2] and J. Kerr[3]

[1] Division of Australian Environmental Studies, Griffith University; Nathan, Queensland 4111, Australia.

[2] Division of Fisheries, CSIRO Marine Laboratories; P.O. Box 120, Cleveland, Queensland 4163, Australia.

[3] Division of Mathematics and Statistics, CSIRO Long Pocket Laboratories, Private Bag No. 3, Indooroopilly, Queensland 4068, Australia.

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Abstract:

The impact of dredging operations on the volute Gastropod (Cymbiolacca pulchra) population of a coral reef atoll (Heron Island, Great Barrier Reef, Australia) was investigated using data from annual surveys of the population and its environment. Comparisons were made of pre-dredging (1984 to 1986), during-dredging (1987) and post-dredging (1988 and 1989) summer densities and size distributions of volutes at eight locations on the reef. There was significant variation among the sites in the pre-dredging years with volutes restricted to four sites characterised by a combination of relatively low bommie cover (< 2%) and high sand cover (> 75%). All four sites were influenced by the dredge plume during dredging operations (September to November 1987 and February 1988). Volute densities declined significantly during dredging (1987) compared to the pre-dredging years. In the following year (1988) the difference was highly significant with zero densities recorded. By 1989 there had been a recovery with no significant difference in the overall density of volutes although the density of small volutes was greater and larger volutes smaller compared to pre-dredging densities. From June 1985 to May 1986 monthly counts were made at all sites to examine seasonal patterns of recruitment. Recruitment into the population occurred over much of the year, though it tended to be higher in the autumn months (March to May), presumably following summer breeding. We suggest that the declines in volute densities were probably due to a failure of recruitment during dredging coupled with a loss of large volutes which may have resulted from natural mortality, emigration, or dredging. The recovery probably followed immigration of large volutes from less affected areas. The environmental factors of percent cover of sand, rock, rubble, coral, bommies and macroalgae were also monitored and there were significant changes in the cover of algae, coral, sand and rubble. These changes are interpreted as covariates rather than causes of observed changes in volute densities. Post-dredging increases in the cover of algae persisted beyond the termination of this study.

Introduction

Cymbiolacca pulchra Sowerby 1825, is a neogastropod of the Family Volutidae. This species occurs in sandy habitats associated with coral reefs of the central and southern Great Barrier Reef, Australia. The Great Barrier Reef is a major centre of volute diversity (Wilson and Gillett, 1979). As in many volutes, there is considerable variation in morphology among different populations of this species, and the Heron Island volute C. pulchra woolacottae, is a form restricted to coral cays of the Capricorn, Bunker and Lady Elliot Islands on the Southern Great Barrier Reef (McMichael, 1959). Apart from some limited studies, mainly on diet (Morton, 1986; Whitehead, 1981), little is known about the ecology of volutes. However, volutes are probably vulnerable to local extinctions following disturbance because of their life history in which there is no free swimming larval stage (Catterall and Poiner, 1987; Hansen,

1978) and, in some species, one or two developing embryos eat all the sibling embryos in the sedentary egg capsule (Bandel, 1976). Furthermore, since volutes are predators of small bivalves and gastropods (Morton, 1986; Ponder, 1970; Weaver and du Pont, 1970; Taylor , 1978; Wilson and Gillet, 1979) , their population densities may be sensitive to generalised perturbations which affect species at lower trophic levels.

During an ecological study (1981 to 1989) of the strombid gastropod Strombus luhuanus (Catterall and Poiner, 1983, 1987; Poiner and Catterall, 1988) data were also gathered fortuitously on the distribution, density and size composition of the Heron Island volute C. pulchra at a series of sites on the Heron Island reef. A rapid decline in volute densities was observed subsequent to the dredging of the Heron Island Harbour and associated beach reclamation works, which took place between 14 September and 14 November 1987, and between the 19 and 21 of February 1988. Around 12, 600 cubic metres of fine sand and consolidated reef matrix was removed from in and around the harbour and associated navigation channel (Fig 1). The beach was extended by impounding the dredge spoil in settlement ponds on the foreshore adjoining the harbour (Anon, 1988). The dredging was associated with a widespread plume of sediment (Fig 1), some of which deposited as a thick layer of fine silt on the beachrock along the southern shoreline of the Island. There were also frequent unplanned leakages of fine silts from the ponds during the dredging works that exacerbated and prolonged the effects of the dredging. Unfortunately no data were recorded on the spatial and temporal extent of dredging-associated changes to either water quality or sediment deposition.

The aim of the study was to assess the potential impact of harbour dredging on the population of C. pulchra and its environment. Pre-dredging, during-dredging and post-dredging volute densities, volute size compositions and environmental characteristics were compared at eight sites on the Heron Island reef flat.

Materials and methods

Study area

Heron Island (Latitude 23^0 26'S; Longitude 151^0 57'E) is a coral cay at the southern end of the Great Barrier Reef which has a large area of intertidal reef flat and a subtidal (approximately 1 to 2.5 m deep) lagoon (Fig 1). Both have a substrate made up of sand and rubble with scattered live and dead coral boulders (bommies); various forms of macroalgae may be present in variable densities (principally species of Caulerpa , Laurencia, Halimeda and Padina in sand and rubble areas, with Sargassum, Hydroclathrus and Turbinaria also growing on the bommies) (Mather and Bennett, 1984). The reef flat is fringed by a reef crest and steep outer slope. Cymbiolacca pulchra occurs on the reef flat in areas where the cover of sand is relatively high, but not in the lagoon (B. Long pers comm). Other characteristics of the Heron Island reef are described in Mather and Bennett (1984). The eight study sites were located to the north (sites 11 and 20), and southeast (sites 41, 42, 44, 45 and 46) of the Island, and on the edge of the lagoon (site 50) (Fig 1). The sites were selected on the basis of their high densities of Strombus luhuanus, a species which typically occurs in areas with a relatively low cover of coral bommies, and where the sand cover is high (Catterall and Poiner, 1983).

Sampling times

Annual volute counting occurred in December and commenced in 1984, continuing until 1989. From June 1985 to May 1986 monthly counts were also made at all sites to examine seasonal patterns of recruitment.

Density measurements

At each site, we measured the density of individuals by means of counts along transects, each measuring 1 m by 5 m. There were 12 permanent transects at each site and the same transect locations were used during successive sampling times.

Divers swam or crawled (low tide) along each transect carrying a 0.5 m X 1.0 m plastic quadrat. Cymbiolacca pulchra individuals were counted in each successive 0.5 m increment in distance resulting in 10 quadrat counts per transect, although all analyses of volute densities were based on single transects as sampling units. Both surface and buried individuals were counted. Buried individuals were found by fanning and / or running fingers through the sand. Shell length (the distance from the shell's anterior end to its apex) was measured in situ to the nearest 5 mm using a ruler. The smallest recorded length was 10 mm.

Substrate

Substrate data were gathered in the first, fourth, seventh and tenth quadrats of each transect. The percent cover of sand (particle size < 10 mm), rubble (particle size 10 to 50 mm), rock (particle size > 50 mm), live coral and bommies were estimated to the nearest 10%. The amounts of tall (> 100 mm high), medium (1 to 100 mm high) and prostrate (rhizomateous growth form, mainly Caulerpa spp. and Halimeda spp.) macroalgae per quadrat were each scored into one of four categories (0 = none; 1 = 0 to 33% cover; 2 = 34 to 66% cover; 3 = 67 to 100% cover). These algal cover data are presented in the results as percentage cover, obtained by allocating each score to the midpoint of its class interval (eg 1 = 16.5%).

Results

Volutes — annual density changes

The annual data comprised counts of volutes from 16 transects at each of the eight sites over seven years. The volute was uncommon and the maximum number found at a site in any year (totalling all transects) was seven. The sites were not homogeneous, and no volutes were ever found at site 50. This site was characterised by significantly low sand cover (66%), high rock cover (21%) and large amounts of prostrate algae (5%) (Tables 1 and 5), and was near the lagoon, well removed from the other sites (Fig 1). Very few volutes (and none less than 40 mm) were sampled from sites 11, 20 and 41 (Fig 2). These three sites had significantly higher bommie cover (> 5%) compared to the rest (Table 1 and 5). This left an apparently homogeneous group of four 'volute' sites (42, 44, 45 and 46). At these volute sites there was a dramatic decline in volute densities following dredging, with an apparent recovery after two years (Fig 3). Statistical analyses to test the significance of this pattern were then conducted as follows.

Volutes — pre-dredging (1984 to 1986)

As the transects were the same from year to year, the problem of the large number of zeros, giving an invalid error, was handled by excluding those transects in which no volutes were sampled in any of the six years. The volutes were also analysed in three size / age categories: (1) all volutes, (2) small volutes (not exceeding 40 mm), and (3) large volutes (> 40 mm).

In order to justify pooling across sites and years (pre-dredging) the variation between sites was compared to the variation between transects within sites. Except in one case, the variation between sites was not significantly greater ($p > 0.05$) than within sites, and it was therefore reasonable to use transect variation and use the data from all transects in which volutes were ever found, as comparable. Possible changes between 1984, 1985 and 1986 were tested by calculating linear and quadratic trends over time. If there was an underlying trend, it would show as a linear effect, but an irregular change would show as a quadratic effect or a mixture of the two. To test for any trends we calculated the changes in volute density per transect between the mean of 1984 and each of the subsequent two years, and used a t-test to examine whether the difference was significantly different from zero. There were no extreme values. The maximum number of volutes recorded in any one transect was three. No linear trends were significant (Table 2). The only significant result was for large volutes restricted to sites 42, 44, 45, and 46 where the means for the three years were: 0.36, 0.12 and 0.63 volutes/transect in 1984, 1985 and 1986 respectively. For all sites, the means were:

0.27, 0.18 and 0.52 volutes/transect in 1984, 1985 and 1986 respectively, and the difference was not significant (Table 2). Although there is some indication that the number of large volutes was depressed in 1985 we considered it reasonable to average the three years for dredging comparisons.

Volutes — dredging comparisons

To examine changes between 1984 to 1986 and the following three years, we calculated the difference in numbers between the 1984 to 86 (pre-dredging) mean and each of the three years 1987 (during-dredging), 1988 (post-dredging) and 1989 (post-dredging) for each transect. The changes in volute density per transect between the average of years 1984 to 1986 (pre-dredging) and each of the three subsequent three years were calculated for the three size / age categories. Again the maximum number of volutes recorded in any transect was three, and so there were no extreme values. A t-test was used to test for differences from zero at the 5% level. Both small and large volutes declined in 1987 compared to the pre-dredging years (Fig 3) and in total the difference was significant (Table 3), but only when all eight sites were included in the analysis. In 1988 the decline was highly significant in both small and large volutes (Table 3) with no volutes sampled that year from any of the sites (Fig 3). By 1989 volute densities did not differ from pre-dredging levels. However, the mean density of small volutes was above the 1984-86 level but the large volutes were still below (although by less than one standard deviation) the pre-dredging level (Table 3).

Habitat change — pre-dredging (1984 to 1986)

Differences among the sites and changes over the three pre-dredging years (1984 to 1986) in the 8 habitat variables (% cover of sand, bommie, rock, rubble and live coral, and the three categories of algae — tall, medium and prostrate) were tested using a nested ANOVA (Zar , 1984). Quadrats (4 per transect) were used as the units of replication in this case. Transects (12 per site) were nested within sites (11, 20, 41, 42, 44, 45, 46 and 50) and sites were fixed. The percent cover data was arcsine square-root transformed (radians), and the Student-Newman-Kuels test was used as a post-priori test for differences between sites, years and site X year interactions. An example of the ANOVA table using sand is presented in Table 4. All the analyses were undertaken using the SAS statistical software package (Anon, 1989).

There were significant site differences for medium algae, prostrate algae, sand, rock, rubble and bommie cover (Tables 1 and 5). There were no significant site X year interactions and no significant year to year differences except for medium algae where 1984 cover was higher than 1985 and 1986 (Table 5). Thus, except for medium algae, we considered it reasonable to average the three years for dredging comparisons.

Habitat change — dredging comparisions

To examine changes in the cover of sand, bommie, rock, rubble and live coral, and the three categories of algae — tall, medium and prostrate between the average of 1984 to 1986 and the following three years (during-dredging 1987, post-dredging 1988, and post-dredging 1989), we calculated the difference in cover between the 1984 to 1986 pre-dredging mean and each of the three following years (during-dredging 1987, post-dredging 1988, and post-dredging 1989) for each of the 12 transects. An ANOVA was used to test for significant differences from zero, and the Student-Newman-Keuls test was used as a post-priori test for differences between the sites. An example of the ANOVA table using 1989 tall algae comparison is presented in Table 6.

There were significant changes in the two categories of algae (tall and prostrate) and for sand and rubble (Table 7, Fig 4, Fig 5). There was a significant post-dredging (1988 and 1989) increase in tall algae at all sites except site 50, however the increases were most pronounced at sites 11 and 20 (Fig 4). In contrast to tall algae there was a during-dredging decline in prostrate algae over all sites (Fig 5). There was also a significant change in the percent cover of sand, rubble and coral (Table 7). The cover of sand decreased during-dredging but increased in both post dredging years (pre- 80.1 %, during- 79.4 %, post-1988 85.6 %, post-1989 85.0 %). In contrast rubble increased during-dredging but decreased in 1988 (pre- 8.7 %, during- 9.1 %, post-1988 2.9 %, post-1989 6.3 %). The coral cover decreased in 1988 (pre- 1.1 %, during- 0.6 %, post-1988 0.4 %, post-1989 0.8 %) (Table 7).

Habitat change — volute sites

Differences among the four volute sites (42, 44, 45 and 46) and changes over the years in the 8 habitat variables (% cover of sand, bommie, rock, rubble and live coral, and the three categories of algae — tall, medium and prostrate) were tested using a similar ANOVA procedure used for all sites (Table 6). The pattern and direction of the changes were the same as for all sites except they were not significant for tall algae and post-dredging 1989 sand. The increase in the cover of rock was significant in post-dredging 1988 (Table 8).

Recruitment

Patterns of recruitment into the population at volute sites were investigated by examining the changes in size distribution from June 1985 to May 1986 (Fig 6). During this period data were collected on 10 occasions spaced approximately one month apart, with a minimum of 12 transects per site Volute numbers were pooled across 50 transects from each sampling time (13 transects in each of sites 44 and 45; 12 transects in sites 42 and 46). Recruitment was not concentrated into a clear seasonal pulse (Fig 6), although there was a tendency for numbers in the smaller size classes to be greatest in autumn / early winter (March to June). Furthermore the largest size class (> 60 mm) occurred only in winter, although the 1985 summer was probably unusual in this respect (Table 2). This suggests an annual cycle with a summer peak of reproduction, followed by recruitment of 10 mm individuals a few months later, that possibly grow to 50 mm or more in one year. Losses from the largest size class would occur because of either mortality or / and emigration. Volutes sampled far from the volute sites were all more than 45 mm (n = 5 volutes; sites 11 and 20, Fig 1).

Discussion and conclusions

C. pulchra life history and movements

In the absence of a pelagic larval phase, which is the major mechanism of dispersal for most marine species, populations are especially vulnerable to local extinctions following major disturbances (Hansen, 1978). Cymbiolacca pulchra, like other extant volute species, probably deposit their eggs within clusters of tough benthic egg cases from which the young hatch directly as miniatures of the adult form (Wilson & Gillett, 1979). However, the limited dispersal capabilities may be partially offset by the potential for rapid active movement seen in volutes (Morton, 1986), although this potential may not be realised in C. pulchra , since individuals spend a large part of their time buried. Only 1% of individuals whose position in the substrate was recorded in this study (n=159) were on the surface, consistent with the impressions reported by Whitehead (1981). Increased emergence may coincide with the turn of the tide from low to flooding (Whitehead, 1981; pers. obs.), as in many other volutes (Wilson & Gillett, 1979) but our data are insufficient to test this. Furthermore, it is also possible that C. pulchra spend more time moving during particular phases of the life-history (subadults for example), or in certain seasons as has been reported for other coral reef gastropods (Stoner et al. , 1988; Catterall and Poiner, 1983; Appeldoorn, 1985)

The limited available data on annual changes in age structure of C. pulchra on Heron Island (Fig. 6) suggest that after reaching approximately 40-50 mm the volutes at the 'volute sites' either emigrated or experienced high mortality. Since the other sites were characterised by much lower densities dominated by large individuals, it seems probable that rates of movement are increased at this size, which may be reached within a year, and that immigration and emigration between local populations would involve mainly larger individuals. The 'volute sites' may be net exporters of mature volutes to other parts of the Heron Island reef.

C. pulchra densities and site effects

There were significant differences in the pre-dredging C. pulchra densities among the sites sampled, with most volutes being concentrated at the four 'volute sites' (42, 44, 45, 46) located close to one another on the reef flat to the southeast of the island. The density at these sites (approximately 0.1 - 0.4 per transect or 0.02 - 0.08 per m^2) seems to be unusually high for this species. The typical density of C. pulchra appears to be less than 0.02 / m^2, although it is considered to be common relative to many other volute species (Coleman, 1981; Wilson and Gillett, 1979). A second volute species, Amoria maculata Swainson 1822, was also found occasionally buried in the substrate during sampling at most sites, but never more than a few individuals across all sites at any sampling time.

The low density of volutes complicated the task of statistical analysis. Each observer took approximately 15 min to sample one transect, so that if density was 0.1 per transect, then 10 transects or 2.5 hours sampling would be needed on average to find one volute. This is broadly consistent with the estimate reported by Whitehead (1981) of three and a half hours of wading per C. pulchra on Northwest Island. This kind of time investment was only possible because most years of the study also targetted another, more common, species (Strombus luhuanus). The use of spatially fixed transects enabled the exclusion from the analysis of the high number of zero-volute transects which may otherwise have invalidated statistical analyses (see Results).

The volute sites also differed from the remaining sites in terms of gross habitat characteristics, having significantly less bommie cover together with a moderately high sand cover (Tables 1 and 5). It is likely that the volute density and recruitment at these sites were influenced by some other factor associated with the complex of between-site environmental differences, possibly through the density of small infaunal bivalves and gastropods. Volutes are active predators which feed mainly on small bivalves and other molluscs (Coleman, 1981; Morton, 1986; Weaver and du Pont, 1970; Taylor, 1978; Ponder, 1970). Inspections and collections of infaunal molluscs at all sites revealed very high densities of several species of small (< 30 mm) cerithid gastropods at the four volute sites, which were rare at the other sites (Rhinoclavis fasciata, R. aspera, R. vertagus, and Cerithium tenelium), as well as relatively high densities of other small gastropods Chrysostoma paradoxum (Trochidae), and Polinices tumidus (Naticidae). The bivalve Fragum fragum (Cardiidae) was common both at the four volute sites and at sites 20 and 41 (cf Fig. 2). Whitehead (1981) recorded C. pulchra eating Fragum fragum at nearby Northwest Island.

Effects of dredging

Although sedimentation from dredging is one of the major sources of reef degradation in the Caribbean and Indo-West Pacific, little is known about how dredging impacts the physical and biological processes operating on reefs (see Rodgers, 1990 for a review). Most studies have investigated the negative effects of dredging on hard corals (Rodgers, 1990).

There have been some investigations of the detrimental effects of dredging on reef fish (Amesbury, 1981; Galzin, 1981) but no studies have focused on reef-flat animals or plants.

Some irregular fluctuations in C. pulchra density occurred during the three pre-dredging years, but these were much smaller in magnitude than changes in density during and after dredging (Fig. 3, Table 3). In December 1987, in the middle of the dredging period, a small though significant decline in density was apparent, which affected mainly the smaller size classes. By the following December (1988), density was so low that no volutes were sampled. It appears that changes to the environment associated with dredging somehow affected the early survivorship of the cohort which would normally have recruited during the summer of 1987 / 88, and that the larger volutes which had been present at the time of dredging either emigrated or died. By the following year (December 1989), total densities had recovered to a stage where they were not significantly different from the pre-dredging mean (Fig. 3, Table 3), although there was a large between-site variation (Fig. 3), and the newly recovered population was dominated by small volutes (volutes 40 mm or less at the volute sites comprised 64% (n=11), 86% (n=7), 23% (n=13), during the three pooled pre-dredging years, 25% (n=4) during dredging in 1987, and 86% (n=14) during recovery in 1989).

Thus the recovery was probably a consequence of immigration of a few adults followed by successful reproduction, probably late in the 1988 / 89 summer, and especially at sites 42 and 46 (Fig 3). Sections of the Heron Island volute population to the north and west of the volute sites should have been much less affected by dredging since the dredge plume was apparently greatly attenuated at about one-third of the way along the Heron Island reef (B. Congdon, M. Preker, J. Nette pers. comm.; Fig 1).

There were significant environmental changes associated with both the during-dredging and post-dredging periods, including changes in the percentage cover of algae, sand and rubble. The generalised picture over all sites was that prostrate algae (which were mainly Caulerpa species) declined dramatically during dredging (1987) but had recovered by 1988, whereas in the post-dredging years (1988, 1989) there was increased sand cover, a decreased rubble cover, and an increase in the cover of tall algae (mainly Sargassum). The prostrate algae mainly grew in the sand and rubble and the tall algae on the bommies. It is likely that the decrease in prostrate algae during dredging was a direct consequence of siltation, which may have temporarily smothered the algae. Increases in sand and decreases in rubble post-dredging may also be a direct consequence of siltation. Post-dredging increases in the cover of tall algae are more difficult to interpret, and may reflect a complex sequence of events involving indirect consequences of dredging. For example, silt deposited on bommies may have produced improved conditions for algal recruitment by mechanisms which could include altering the microsite physical structure, nutrient status, or interactions with corals. There was a significant decrease in coral cover in 1988 (Table 7), which may also have favoured algal recruitment.

There were also other widespread environmental changes unrelated to dredging which occurred during the period of this study. During February 1987 there was a widespread coral bleaching and death on the Heron Is. reef flat (M. Preker, C. F. Catterall pers. comm.), and there was also unusually cold weather in June / July of 1989 . These could have contributed to 'post-dredging' changes, or interacted with the dredging effects. For example, an earlier loss of live coral on bommies may also have resulted in increased recruitment success of tall algae. However, the precise timing of the significant changes in volute density and environmental variables apparent in our data is most consistent with a scenario in which the majority of changes were caused by the dredging events between September 1987 - February 1988.

It is however, difficult to make direct causal connections between dredging-associated changes in volute densities and concurrent changes in gross environmental variables such as algal and substrate cover types. Newly hatched volutes may have been smothered. Alternatively, the dredging could have caused large temporary reductions in the infaunal mollusc community which the volutes eat, either by direct smothering or indirectly by affecting the supply of algae and detritus consumed by the infaunal molluscs. Rapid recolonisation by these small infaunal molluscs is likely because of their pelagic larval stage. Siltation has been implicated in the declines in the density of juvenile spiny lobsters (Panulirus argus) in the Florida Keys, USA by affecting recruitment, as well as the density of their prey (gastropods and amphipods) in the preferred juvenile micro-habitat; clumps of the algae Laurencia sp. (Herrnkind *et al.*, 1988).

Whatever the causal mechanisms, the data indicate that the dredging resulted in widespread perturbation to the reef flat community, including that reflected in the volute C. pulchra population. Furthermore, many components of this community required two or more years to recover to predredging levels. Whether temporal variability or stability (sensu Connell and Sousa, 1983; Beddington, 1984) following this recovery are comparable with those prior to dredging is a question beyond the scope of the present study, and one which would require at least a sound longer-term set of monitoring data pre-dredging, for comparison with a similar set post-dredging.

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Tables

Table 1: Substrate characteristics (% cover of sand, rubble, rock, live coral and bommie) of the 8 sites (Fig 1) sampled annually in December, and averaged over the three years (1984 to 1986) prior to dredging. The amounts (mean of the 4 categories converted to % cover) of tall, medium and prostrate algae are also presented. The standard errors (s.e.) of the estimates are also shown; n = 36 (12 transects / site X 3 years).

Cover	Site							
(%)	11	20	41	42	44	45	46	50
Bommie	12.2	8.9	5.3	0.3	1.1	1.4	0.7	1.5
s.e.	2.4	1.2	1.8	0.3	0.3	0.1	0.3	0.7
Sand	73.9	83.9	87.2	81.3	86.6	77.9	88.0	65.6
s.e.	2.8	1.9	2.3	4.0	1.6	0.7	2.9	1.8
Live coral	2.7	2.4	0.3	0.0	0.6	0.9	0.0	1.8
s.e.	1.8	1.1	0.2	0.0	0.1	0.5	0.0	0.9
Rubble	9.4	5.1	5.6	12.8	6.7	9.4	9.2	11.7
s.e.	0.1	0.9	1.1	3.5	2.2	0.6	3.0	1.5
Rock	13.9	8.5	6.9	5.8	6.0	11.8	2.9	20.5
s.e.	1.8	1.9	1.5	1.0	1.0	1.0	0.5	1.3
Tall algae	0.0	0.1	0.1	0.0	0.0	0.1	0.3	0.0
s.e.	0.0	0.1	0.1	0.0	0.0	0.1	0.3	0.0
Medium algae	13.4	8.3	5.3	9.7	6.7	8.8	6.9	12.5
s.e.	2.5	1.9	1.3	1.0	1.0	2.3	0.5	1.4
Prostrate algae	4.3	4.0	1.3	1.7	3.9	2.4	2.1	4.7
s.e.	0.12	0.5	0.5	0.9	1.1	0.3	0.9	2.1

Table 2: Cymbiolacca pulchra, comparisons of the changes in December densities at all eight sites and the four volute sites (42, 44, 45 and 46) from 1984 to 1986 of small (not exceeding 40 mm), large (>40 mm) and all volutes tested (t-test) for linear and quadratic trends over the 3 years. The standard error (s.e.) of the change, the t-value (t) and the sample size (n, excluding those transects in which no volutes were sampled in any of the three years) are also presented. (* = $p < 0.05$).

Volute size	Trend	All sites				Volute sites			
		Change	s.e.	t	n	Change	s.e.	t	n
Small	Linear	-0.17	0.13	1.32	15	-0.17	0.13	1.32	15
	Quadratic	0.01	0.06	0.19	15	0.01	0.06	0.19	15
Large	Linear	0.10	0.13	0.76	15	0.09	0.18	0.52	11
	Quadratic	0.08	0.05	1.52	15	0.12	0.06	2.19*	11
All	Linear	-0.04	0.10	0.40	26	-0.07	0.11	0.62	22
	Quadratic	0.05	0.05	1.00	26	0.07	0.06	1.18	22

Table 3: Cymbiolacca pulchra, comparisons of the changes in the pre- (1984 to 86), during- (1987) and post-dredging (1988 and 1989) December densities of small (not exceeding 40 mm), large (>40 mm) and all volutes for both all eight sites and the volute sites (42, 44, 45 and 46). Differences between pre-dredging versus during-dredging (1987), pre-dredging versus post-dredging (1988) and pre-dredging versus post-dredging (1989) were tested using a t-test. The standard error (s.e.) of the change, the t-value (t) and the sample size (n, excluding those transects in which no volutes was sampled in any of the six years) are also presented. (+ = $p<0.10$; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$)

Volute size	Trend	All sites				Volute sites			
		Change	s.e.	t	n	Change	s.e.	t	n
Small	1987	-0.22	0.11	2.00+	15	-0.22	0.11	2.00+	15
	1988	-0.29	0.07	4.01**	15	-0.29	0.07	4.01**	15
	1989	0.24	0.21	1.16	15	0.24	0.21	1.16	15
Large	1987	-0.16	0.12	1.33	15	-0.15	0.16	0.96	11
	1988	-0.29	0.06	5.23***	15	-0.33	0.06	5.20***	11
	1989	-0.09	0.15	0.59	15	-0.24	0.14	1.78	11
All	1987	-0.22	0.10	2.12*	26	-0.23	0.12	1.88	22
	1988	-0.33	0.07	4.97***	26	-0.36	0.08	4.79***	22
	1989	0.09	0.15	0.60	26	0.05	0.16	0.27	22

Table 4: ANOVA of the differences among the sites and changes over the three pre-dredging years (1984 to 1986) in the percent cover of sand. Transects (12 per site) were nested within sites (11, 20, 41, 42, 44, 45, 46 and 50) and sites were fixed (df = degrees of freedom; SS = sums of squares; MS = mean square; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; ns = non-significant; means underlined (bottom part of Table) were not significantly different).

Source	df	SS	MS	F-Value	Significance
Model	111	37.94	0.34	4.45	***
Error	1029	78.97	0.08		
Total	1140	116.91			

Tests of hypotheses using the Type II MS for Transect (Site) as the error term:

Source	df	Type II SS	F-Value	Significance
Site	7	13.12	7.17	***
Year	2	1.04	1.98	ns
Site X Year	14	0.90	0.25	ns

Student-Newman-Keuls Test for Year

	1984	1985	1986
Mean =	1.22	1.17	1.45

Student-Newman-Keuls Test for Site

	46	41	44	20	42	45	11	50
Mean =	1.28	1.28	1.28	1.25	1.18	1.13	1.09	0.97

Table 5: Summary of the results of the ANOVA's of the differences among the sites and changes over the three pre-dredging years (1984 to 1986) in the percent cover of sand, bommie, rock, rubble and live coral, and the three categories of algae — tall, medium and prostrate. Transects (12 per site) were nested within sites (11, 20, 41, 42, 44, 45, 46 and 50) and sites were fixed The % cover data was arcsine square-root transformed (radians). Site and year codes are listed from greatest to smallest. (* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; ns = non-significant; sites codes underlined were not significantly different). See Table 4 for an example of the ANOVA.

Habitat variable	Source of variation		
	Site	Year	Site X Year
Algae covers			
Tall	ns	ns	ns
Medium	*** 11 50 42 45 20 46 44 41	** 84 86 85	ns
Prostrate	** 50 11 20 44 45 46 42 41	ns	ns
Substrate cover			
Sand	*** 46 41 44 20 42 45 11 50	ns	ns
Rock	*** 50 45 11 44 20 42 41 46	ns	ns
Rubble	*** 50 42 45 46 11 44 41 20	ns	ns
Live coral	ns	ns	ns
Bommie	*** 11 20 41 45 50 44 46 42	ns	ns

Table 6: Comparision of the changes in the pre-dredging (1984 to 1986) and post-dredging 1989 cover of tall algae for all sites (11, 20, 41, 42, 44, 45, 46 and 50) with transects as the unit of replication, and 12 transects per site. Differences between pre-dredging and post-dredging values were tested using ANOVA. (df = degrees of freedom; SS = sums of squares; MS = mean square; * = p < 0.05; ** = p < 0.01; *** = p < 0.001; ns = non-significant; means underlined (bottom part of Table) were not significantly different).

ANOVA — Change in tall algae (1984 to 1986 minus 1989)

Source	df	SS	MS	F-Value	Significance
Site	7	1.26	0.18	3.34	**
Error	88	4.75	0.05		
Total	95	6.01			

Student-Newman-Keuls Test for Sites

	50	44	46	41	45	20	42	11
Mean =	<u>0.00</u>	<u>- 0.02</u>	<u>- 0.02</u>	<u>- 0.06</u>	<u>- 0.10</u>	<u>- 0.17</u>	<u>- 0.17</u>	- 0.38

Table 7: All sites (11, 20, 41, 42, 44, 45, 46 and 50) — summary of the results of the ANOVA's comparing the changes in the substrate cover (sand, bommie, rock, rubble and live coral, and two categories of algae — tall and prostrate) betweeen the pre-dredging years (1984 to 1986) and during-dredging (1987) and, betweeen the pre-dredging years (1984 to 1986) and each of the post-dredging (1988 and 1989) years. The % cover data were arcsine transformed. The direction (increase or decrease) of the change over all sites is given in brackets and site codes are listed from greatest to smallest change with the direction of the change at each site indicated by + or -. (* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; ns = non-significant; sites codes underlined were not significantly different). See Table 6 for an example of the ANOVA.

Habitat variable	Year		
	1987	1988	1989
Tall algae	ns	*** (increase) 50 45 42 41 44 46 20 11 + + + + + + +	** (increase) 50 44 46 41 45 20 42 11 + + + + + + +
Prostrate algae	** (decrease) 50 11 20 44 45 46 42 41 - - - - - - - -	ns	ns
Sand	** (decrease) 44 46 45 42 11 50 20 41 + + + + + - - -	** (increase) 44 20 50 45 46 11 41 42 - + + + + + + +	** (increase) 44 42 46 45 20 50 11 41 - - - + + + + +
Rock	ns	ns	ns
Rubble	* (increase) 41 20 50 46 42 45 11 44 - - + + + + + +	**(decrease) 42 46 41 45 20 44 50 11 - - - - - - - -	ns
Live coral	ns	ns 20 11 50 44 45 42 46 41 - - - - - - - +	ns
Bommie	ns	ns	ns

Table 8: Volute sites (42, 44, 45 and 46) — summary of the results of the ANOVA's comparing the changes in substrate cover (sand, bommie, rock, rubble and live coral, and two categories of algae — tall and prostrate) betweeen the pre-dredging years (1984 to 1986) and during-dredging (1987) and, betweeen the pre-dredging years (1984 to 1986) and each of the post-dredging (1988 and 1989) years. The % cover data were arcsine transformed. The direction (increase or decrease) of the change over all sites is given in brackets and site codes are listed from greatest to smallest. change with the direction of the change at each site indicated by + or -. (* = p < 0.05; ** = p < 0.01; *** = p < 0.001; ns = non-significant; sites codes underlined were not significantly different).

Habitat variable	Year		
	1987	1988	1989
Tall	ns	ns	ns
Prostrate	* (decrease) 44 45 46 42 - - - -	ns	ns
Sand	* (decrease) 44 46 45 42 - - - -	*** (increase) 44 45 46 42 + + + +	ns
Rock	ns	** (increase) 42 45 46 44 - + + +	ns
Rubble	* (increase) 46 42 45 44 + + + +	**(decrease) 42 46 45 44 - - - -	ns
Live coral	ns	ns 20 11 50 44 45 42 46 41 - - - - - - - +	ns
Bommie	ns	ns	ns

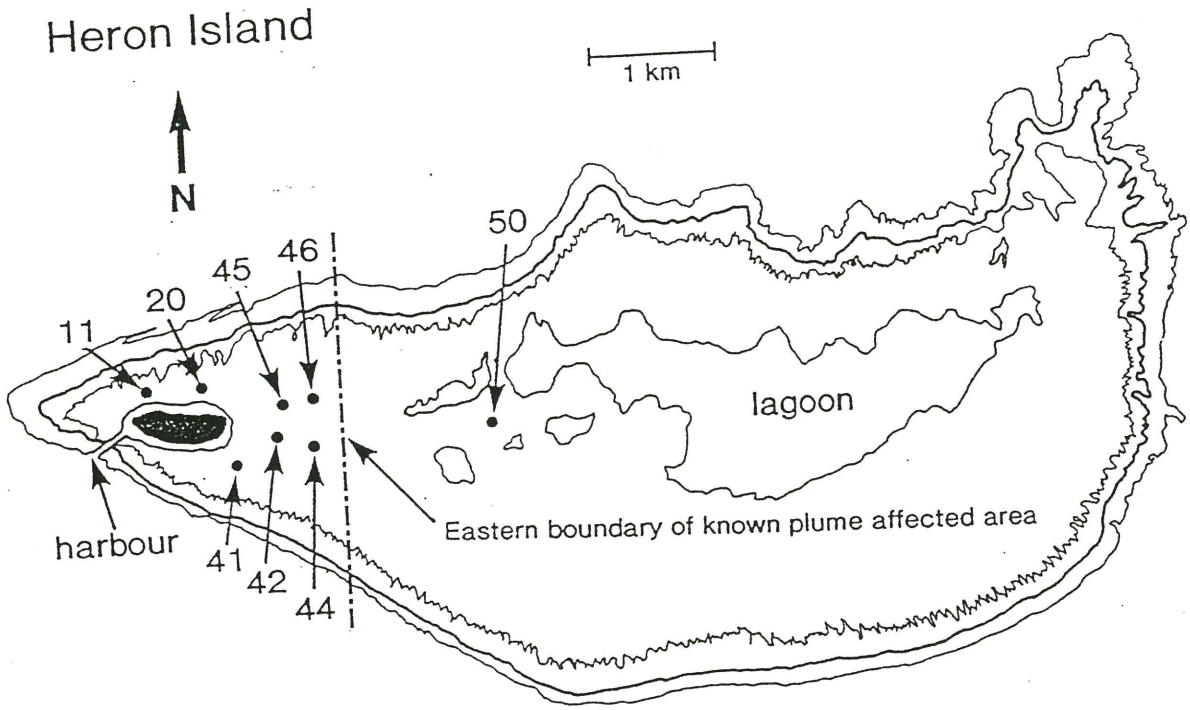

Figure 1: Heron Island (Latitude 23^0 26'S; Longitude 151^0 57'E) showing the reef flat, the lagoon, the location of the 8 study sites, the dredged harbour, and the known western boundary of the dredge-plume affected areas.

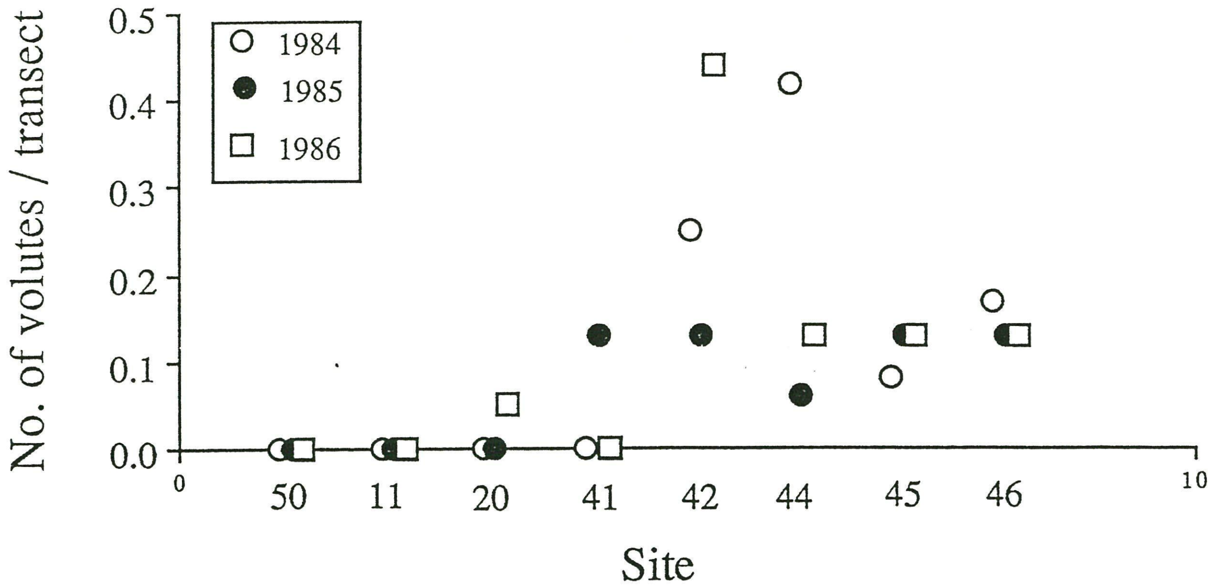

Figure 2: Cymbiolacca pulchra, pre-dredging mean volute December densities (number per transect) for each site, in 1984, 1985 and 1986.

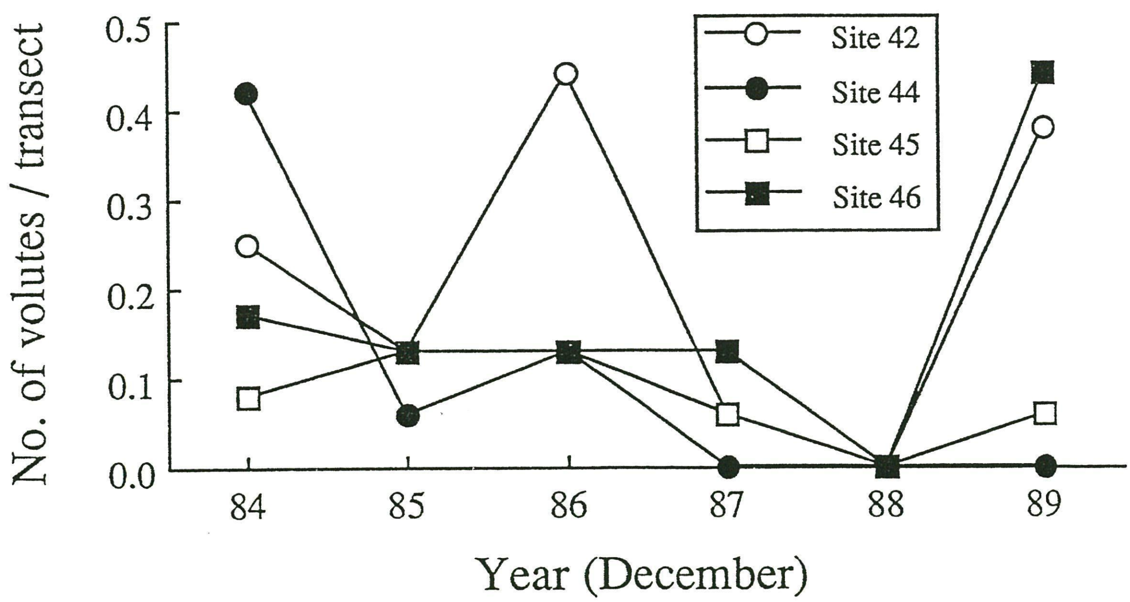

Figure 3: Cymbiolacca pulchra, 1984 to 1989 — Mean volute December densities (number per transect) for the four volute sites (42, 44, 45 and 46).

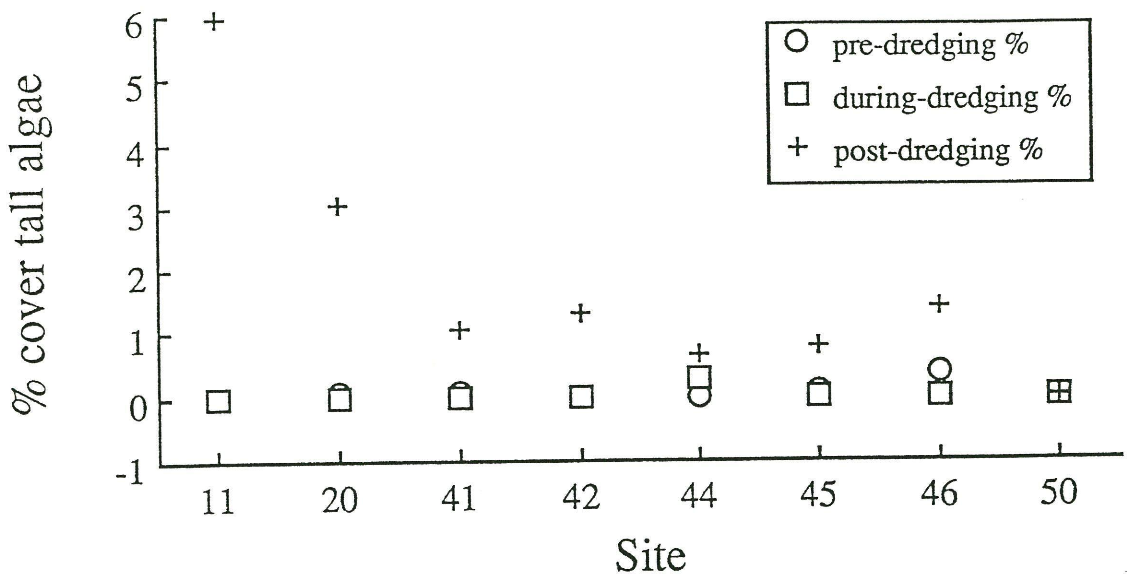

Figure 4: Pre-dredging, during-dredging and post-dredging mean percent cover of tall algae for each of the eight sites.

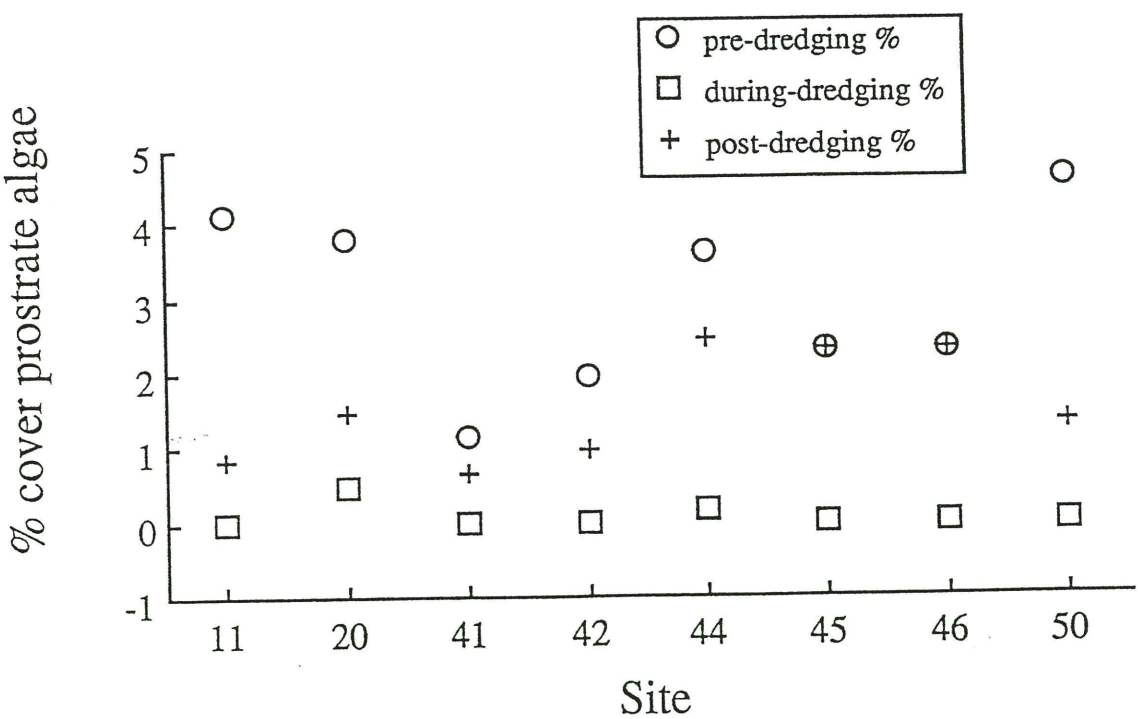

Figure 5: Pre-dredging, during-dredging and post-dredging mean percent cover of prostrate algae for each of the eight sites.

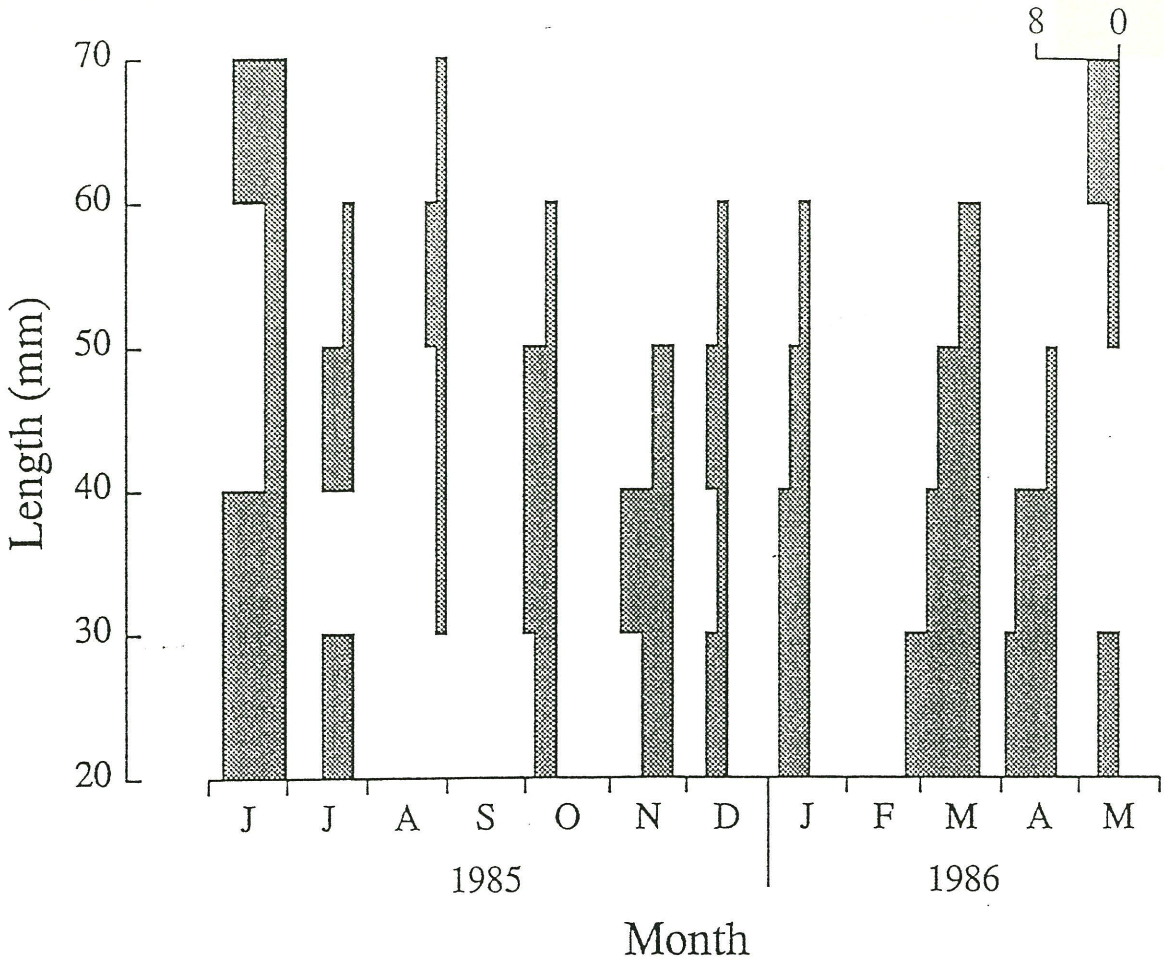

Figure 6: Cymbiolacca pulchra, volute sites (42, 44, 45 and 46) — Numbers of volutes recorded in each of five length classes (< or = 30 mm, 31 to 40 mm, 41 to 50 mm, 51 to 60 mm, > 60 mm), at 10 sampling times spanning the year June 1985 to May 1986.

Recommendations to GBRMPA

1. No action is necessary regarding the Heron Island volute, *Cymbiolacca pulchra*..

2. Implement cost-effective annual environmental monitoring programs which aim to measure both changes in substrates, and changes in the abundance and distribution of the dominant benthic plants and animals on 'high risk' reefs within the Great Barrier Reef Marine Park, such as Heron Island.

3. There should be on-site monitoring of the details of potential disturbances such as dredging; with the data and results readily available. For dredging works this should include:
   - the distribution of areas of mechanical damage (ie dredged areas);
   - the spatial and temporal distribution of the sediment plume;
   - concentrations of suspended materials in the plume;
   - sediment deposition rates and extent (measured or modelled) from the plumes;
   - chemical analysis of the dredge plumes;
   - pre-dredging, during-dredging and post-dredging monitoring of both changes in substrates, and changes in the abundance and distribution of the dominant benthic plants and animals in dredged areas, plume-effected areas and control areas.

4. Repeat of our post-dredging environmental data collection programme in December 1990 and 1991 to compare to the pre-dredging set, in order to identify the recovery time in relation to the disturbance described in this report. This is recommended in view of the fact that post-dredging changes in algal cover and substrate persisted beyond the termination of the present contract. This would cost between $5,000 and $10,000 / year.

5. Great Barrier Reef Marine Park Authority should reassess the advantages and disadvantage of ocean dumping or ocean broadcast-spreading of dredge spoils. This should take into account the intertidal impacts associated with dredging and with the settlement ponds demonstrated both in this study and in others, when compared with published evidence of relatively low impacts associated with ocean dumping (supporting literature for the latter can be provided).