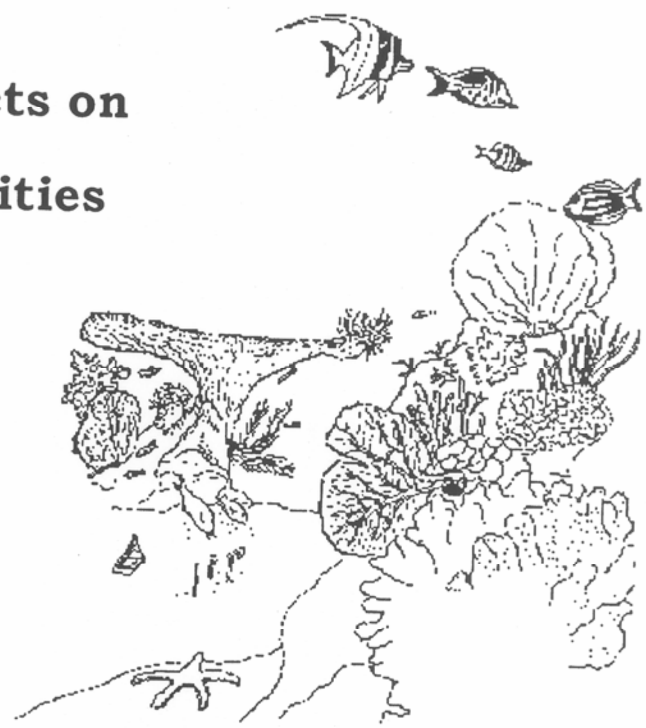
South Pacific Regional Environment Programme

Preliminary Report on the Pilot Dredging Project - Funafuti, Tuvalu:

Assessment of Ecological Impacts on Lagoon Communities



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EXECUTIVE SUMMARY

This report summarises the main preliminary results of an ecological impact assessment of the Pilot Dredging Programme carried out in Funafuti Lagoon, Tuvalu, between March 1992 and August 1993. The aim of the project was to examine the impact of a small-scale dredging operation, as part of a feasibility study for the in-filling of borrow pits on Fogafale with lagoon sediments. A three-stage sampling design involving two surveys prior to dredging, two during, and two after dredging has been completed to the end of the dredging phase (4 surveys). The sampling design included a grid of nine sites (200m apart) at the primary impact site and three control sites along the fringing reef, and a further impact and control site on off-shore patch reefs in the lagoon. This sampling protocol enabled us to determine pre-existing patterns in the biota, measure short-term impacts evident during the dredging period only, and assess any effects that develop on a longer-term basis. The intertidal reef platform, the subtidal reef top and slope, and adjacent soft-sediment habitats were sampled, encompassing all major habitats likely to be affected, either by sediment deposition or increased turbidity. The abundance and diversity of the dominant organisms within each habitat were recorded including reef-associated fishes (wrasses, surgeonfish and butterflyfish), all corals and macro-algae, toxic dinoflagellates, mobile reef-based invertebrates, intertidal invertebrates and soft-sediment macrofauna (molluscs, echinoderms and crustaceans).

This preliminary report presents the major findings for organisms on the subtidal reef top and slope, indicating: (1) Quantitative differences between the primary impact sites and the control sites prior to any dredging; (2) Qualitative observations of coral stress during dredging operations; and (3) Effects of dredging on either abundance or diversity detected by the end of the 4th survey.

The pre-dredging surveys indicated major differences among impact and control sites prior to any dredging activity, which affected approximately one third of the comparisons made. The primary dredge site (D) was characterised by higher levels of algal cover and densities of fishes and invertebrates associated with algae or sediments, and lower levels of coral cover and fish species associated with live-coral habitat. The offshore impact site, Vaiaku Reef, was more similar in reef-community structure to the controls. These results suggest that the area in the vicinity of the lagoon fringe near Fogafale was already heavily impacted prior to this dredging operation.

Coral stress was observed at Vaiaku reef in June 1993 during the dredging phase. This included heavy production of mucus, bleaching of coral colonies and partial mortality of some coral colonies. This was only in evidence during a period when a turbid plume of water from the dredge was being pushed over the reef.

An effect of dredging (a greater change in abundance or diversity at impact sites relative to controls) was detected in 22% of the comparisons made, with 78% of species being unaffected. The effects were divided between 15% of comparisons which showed a decrease in abundance or diversity, and 7% that exhibited an increase. In most cases the effects were quite small in magnitude, when compared with the pre-existing differences between dredge and control sites. In general, species showing a decline were those that were already lower in abundance at

control sites, suggesting that the impact of dredging was reinforcing historic impacts in the vicinity of the dredging operation. This included coral species and fishes associated with live coral habitat. Species that increased were those typically associated with algal-dominated or bare rock substrata, such as algae and some fish and invertebrates. Some sensitive coral species were already scarce in the region of dredging, so no decline was possible. The greatest impacts were recorded Vaiaku Reef where coral cover was higher at the beginning of the study and some coral stress was observed.

Conclusions concerning the effects of dredging must be treated with caution as the longer term impacts or recovery are unknown, and we have not yet examined the spatial extent of the impact on the grid or the other habitats. From the present graphical analysis, the impact of dredging does not seem to be severe and is difficult to separate unequivocally from the pre-existing impacts on the habitat. The extent of the pre-existing impacts places limits on the magnitude of the compounding effects due to dredging at this location.

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1. INTRODUCTION

Background

In March 1992 the South Pacific Applied Geoscience Commission (SOPAC) implemented a pilot dredging scheme in Funafuti, Tuvalu. The purpose of the dredging operations, which were to continue for most of the easterly season of that year was to collect and move approximately 25,000m^3 of sediments from Funafuti Lagoon to fill borrow pits created during the construction of an aircraft runway on the island of Fogafale. In practice, the dredging works continued until the end of August 1993, with a recess during the 1992/1993 westerly season. The Pilot Dredging Project itself was implemented with two main objectives:

- to test the feasibility of using lagoon materials for filling the borrow pits; and
- to monitor the effects of the dredging and filling programme on the environment.

Halimeda and Foraminifera sands (formed from the skeletal remains of calcareous algae and protozoans) were collected from the lagoon floor using an air-lift suction dredge which loaded material into a hopper barge. The loaded barge was then pushed ashore and unloaded using a front-end loader before being stock-piled near the landing site. A tractor trailer was then used to move materials to the target mangrove pit located at the northern end of Funafuti Runway.

Several monitoring projects were implemented to examine effects of dredging on the environment. These included effects on lagoon and beach sediments, water quality/clarity and lagoon organisms. This report deals with preliminary findings from the measurement of impacts of the dredging on lagoon flora and fauna.

Issues

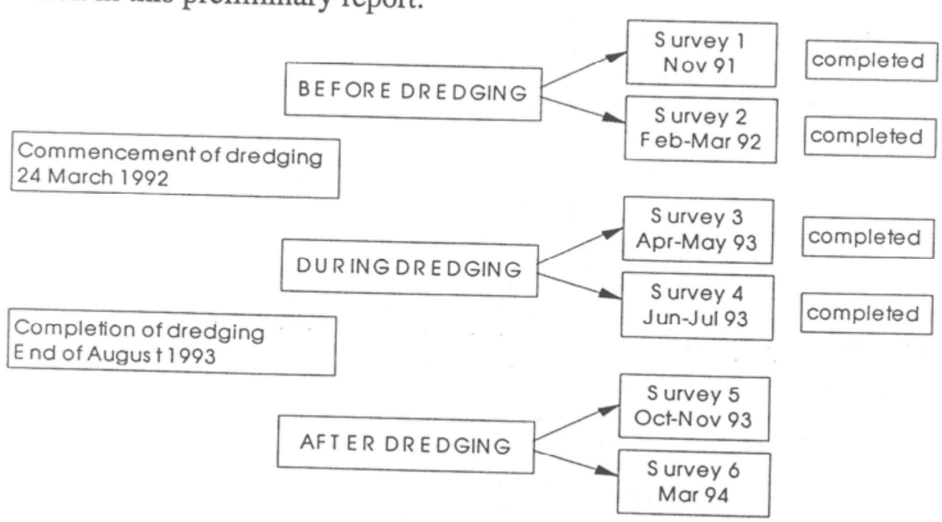
Coral biologists have long argued that corals are susceptible to turbidity and light attenuation in their environment, with some species tending to be more tolerant of sedimentation and tending to occupy continental near-shore reefs where clear waters are rare (Bull, 1982; see review by Craik & Dutton, 1987), and others being found only in areas with very little turbidity. Within this partitioning of species between silt-tolerant and clear-water species, it has also been stated many times that any activities which would further increase the local siltation levels (human development, cyclones etc) would lead to damage to the corals normally found within any one area (Fisk, 1983; Cortes & Risk, 1985). The effects of development on coral reefs is of increasing concern in the Pacific where there is a delicate balance between human progress and preservation of the coral reef systems. It is clear that studies on the effects of particular developments on reef communities are of great importance for coral reef management.

Although studies which examine the overall changes in coral communities in response to environmental impacts are relatively common (e.g. Brown & Howard, 1985; Carpenter & Maragos, 1989) only a small proportion of these have focussed on the effects of dredging or the dumping of sediments (Pastorok & Bilyard, 1985; Rogers, 1990). A few studies which focus on other forms of development, such as increasing run-off adjacent to island and continental farming communities and other activities which disrupt the natural coastal and hinterland vegetation, are also of relevance here. The shortage of literature on similar projects is probably largely because most major ports around the word have tended in the past to be concentrated in temperate and cooler climes, with large-scale port developments only recently expanding to the tropics.

Early studies on the effects of dredging on adjacent coral communities were often approached only qualitatively or semi quantitatively with little opportunity for accurate descriptions of the effects. Brock, *et al.,* (1966) reported on the effects of large-scale dredging on Johnston Atoll (700 acres dredged). Declines due to sedimentation of up to 40% loss in biotic cover affected 1,100 acres of coral reef. More recent quantitative studies have come up with opposing results. In some areas, or types of operations, impacts are great, leading to large losses in coral cover (e.g. Dodge & Vaisnys, 1977; Chansang, *et al.,* 1981). In other dredging assessments very few impacts on coral communities were detected (Mapstone, 1990; Stafford Smith *et. al.*, 1993). In one study, the turbidity associated with dredging was considered small in relation to that observed during natural disturbance events (Zolan & Clayshulte, 1981). The presence of regular periods of natural turbidity (cyclones, monsoons) and/or differences in natural tolerance in coral species are likely to play an important role in the predicted effects of dredging activities for any particular coral reef community and would help to explain some of the apparently opposing results obtained by different workers.

Aims of this study and report

In this report, we describe results obtained to date on our assessment of impacts of dredging on the coral reef communities at Funafuti, Tuvalu. The complete impact assessment will occur in three phases: two surveys carried out prior to the commencement of dredging (Surveys 1 and 2), two surveys during dredging (Surveys 3 and 4), and two surveys to be conducted in the months following the completion of dredging (Surveys 5 and 6). To date, only the first four surveys have been completed for inclusion in this preliminary report:



The specific aims of the results presented here were to:

1. Describe any pre-existing conditions in fish, coral, algal and other invertebrate abundances on the subtidal reefs in Funafuti Lagoon prior to the commencement of dredging;
2. Monitor, by qualitative observations, levels of coral stress during the dredging works; and
3. Compare data on abundances collected from the vicinity of dredging during Trips 3 and 4 with pre-dredging surveys (1 and 2) and control areas to determine whether any short-term impacts of dredging have occurred on lagoon communities

Data to be collected in the final two surveys are aimed at addressing longer-term effects and recovery from any impacts of dredging.

2.2 Methods

2.2.1 Sites

In all surveys we examined 14 sites in the eastern portion of Funafuti Lagoon, adjacent to Fogafale. The sites were divided into two types based on their relationship to the island. "Fringing" or "contiguous" reefs were those whose structure followed the outline of the island, while "bommies" or "patch reefs" were small roughly circular reefs which were surrounded by lagoon sediments and/or deep water and were not connected with the island by a continuing reef system (Figure 1).

The sites were further divided, *a priori*, into "Impacts" and "Controls". Impact sites were those directly surrounding the dredge line - those most likely to experience and manifest any impacts should they occur. One of these was located at the Dredge Site (Figures 1 & 2), and a further eight were surveyed in a grid four on either side of the dredge line at intervals of 200m (hereafter the "impact grid"). Three of the sites surveyed were Controls, two to the north (NC1 = "Pig Farm" and NC2 = "Hideaway") and one to the south of the dredge line (SC = "Muli Malai"). This design allows us not only to detect impacts, but also to measure the linear extent away from the dredge site that any effects might extend. The two patch reefs surveyed included one considered an impact site located out from the impact grid about 200m off the dredge line called "Vaiaku Reef" (VR) (Figure 1), and another considered a control about 1700m out in the lagoon, "Lakau Reef" (LR).

In this report we present a preliminary graphical analysis of the differences between the primary dredge site (D) and control sites; and differences between Vaiaku Reef and control sites.

Figure 1: Map of Fogafale Island, Funafuti showing the location of all major sites surveyed.

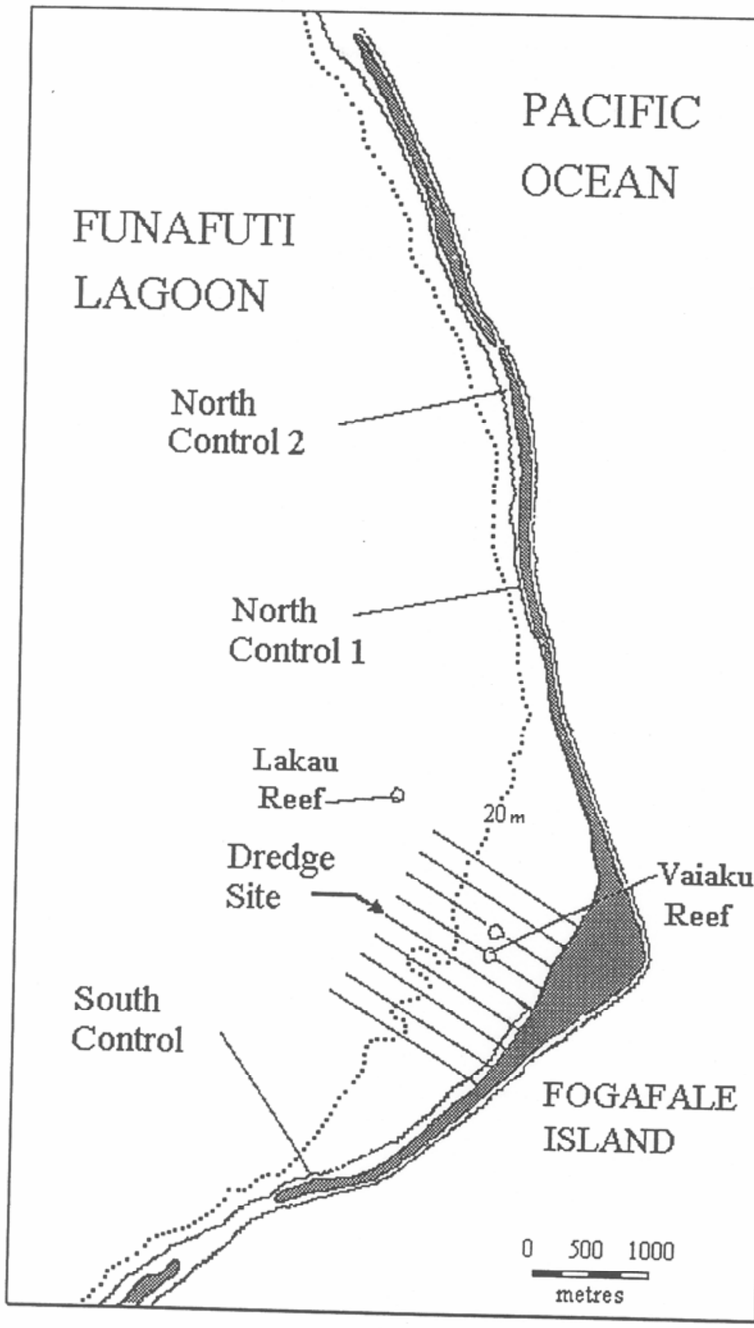
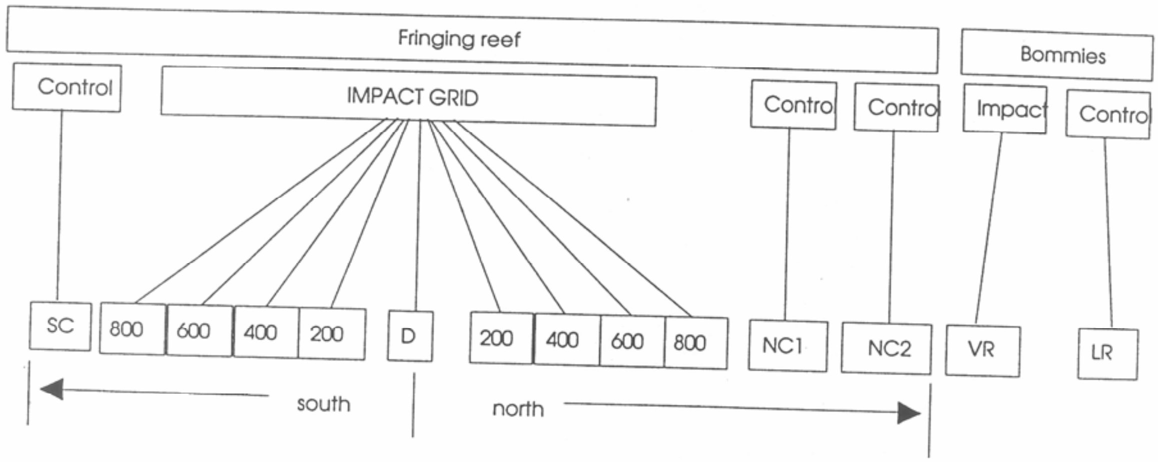


Figure 2: Survey design used in this assessment. The figure shows the distribution of all sites surveyed in relation to their categorisation as "impact" or "control" for fringing reef area and isolated bommies (patch reefs).



2.2.2 Qualitative Observations

The condition of corals was monitored during Surveys 3 and 4 while dredging was occurring. The purpose of this work was to examine any immediate stresses of dredging on the 'health' of corals, the group most likely to be immediately responsive to dredging impacts. Observations were made at all sites during the formal surveys and were supplemented with additional spot checks from time to time. Corals throughout each site were examined for any evidence of stress normally cited for turbidity damage (Stafford Smith, 1993; Stafford Smith & Ormond, 1992), including:

- unusually heavy production of mucus (usually rolling off in sheets)
- bleaching (light to very heavy)
- partial to complete mortality.

If any of these responses were found in more than one or two corals, the site was inspected more heavily for evidence of crown-of-thorns starfish or predatory gastropod damage, infestations by worms or other diseases, and turbidity. All observations were recorded as notes and repeated throughout the trip if a site was found to be suspect.

2.2.3 Quantitative Survey Methods

The quantitative section of the work was carried out in six lagoon habitats, wherever they were present at a site:

(i) Intertidal area
(ii) Reef

Reef top
Reef slope

(iii) Lagoon sediment
Reef Edge
at depth of 50'
at depth of 70'

Within each habitat we surveyed the abundance as counts per unit area, as percent cover, or sometimes both, of fish, corals, other invertebrates, and algae (including the ciguatera-causing *Gambierdiscus toxicus*). Table 1 summarises those habitats and species surveyed at each of the 14 sites.

Table 1: Summary of the habitats, species and methods used to survey each location during each survey.

HABITAT	SUB-HABITAT	SPECIES / VARIABLES	METHOD	REPLICATES	SITES
Intertidal	High tidal level	% cover sediments % cover algae	10m transect with 40 points	5	all except bommies
		Molluscs Crustaceans	1 m sq quadrat	5	
Reef	Reef Slope	Wrasses Surgeonfish Butterflyfish	30x10m transects	5	all
		% cover algae % cover corals counts of corals % cover sediments	20m transects with 40 points	5	all
	Reef Top	Wrasses Surgeonfish Butterflyfish	30x10m transects	5	all
		% cover algae % cover corals counts of corals % cover sediments	20m transects with 40 points	5	all
		G. toxicus counts (ciguatera)	Yasumoto's method	5	Dredge plus three fringing controls
Lagoon sediments	Reef edge	Molluscs Echinoderms Crustaceans	cores	5	all except bommies
	50' deep	Molluscs Echinoderms Crustaceans	cores	5	Dredge plus three fringing controls
	70' deep	Molluscs Echinoderms Crustaceans	cores	5	Dredge plus three fringing controls

Fish Communities

Approximately 400 species of reef fishes belonging in 64 families have been recorded from Tuvalu (Jones, *et al.*, 1991). For the purposes of detecting impacts of dredging on lagoon fauna, including fisheries stocks, we selected three families to be censused. The families selected were the wrasses (*Kiole*), surgeonfishes (*Pone*) and butterflyfishes (*Moepepe*) which totalled to 75 species. These families were chosen because together they included species which display all major life history characteristics encountered in most reef fishes. They were also chosen because they are numerically dominant, important in local subsistence fisheries and are those most likely to respond to any reef degradation.

All fishes belonging to the nominated species were surveyed in transect lines laid out on the reef slope and reef top at all locations. Transects were 30 metres long and 10 metres wide and laid out on the substratum randomly using fibreglass tape measures. Each tape was censused visually after a five minute wait to allow fishes to return to their normal activities after the tape was run out. Five replicate tapes were censused at each location and habitat during each trip.

Table 2: Families of fishes included in surveys.

FAMILY	ENGLISH COMMON NAME	TUVALUAN COMMON NAME	NUMBER OF SPECIES	REASON INCLUDED
Labridae	Wrasses	Kiole	37	Generalist feeders and habitat responders, within this family all major fish habits found
Acanthuridae	Surgeonfishes	Pone	21	Algal feeders, likely to respond positively to increases in algal cover if reef degrades
Chaetodontidae	Butterflyfishe s	Moepepe	17	Coral feeders, likely to respond negatively to decreases in coral cover if reef degrades

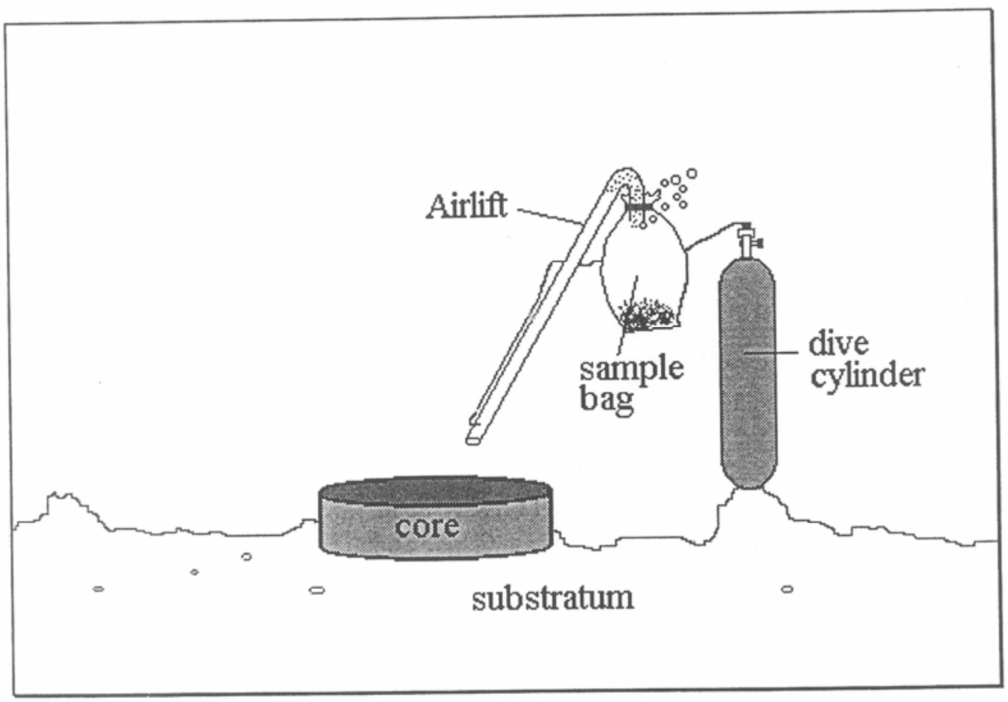
Corals, Algae and other reef Invertebrates

Corals and algae were examined usually in terms of percent cover on the reef, although some types of corals were also censused by counts of the number of individuals per unit area. Percent cover was estimated using 20m transects laid out on the reef along which were marked 40 points. The substratum type, coral or algal species found under each of the points was then recorded and used to derive an estimate of percent cover. Counts of numbers of corals and other reef invertebrates (such as sea cucumbers and corallivorous snails) were made in 20x2m transects. All transects were laid out randomly in the Reef Slope and Reef Top habitats at all locations and during all surveys.

Lagoon Infauna

Counts of molluscs and crustaceans were obtained in lagoon sediments collected adjacent to the reef at all fringing reef sites and at the Dredge and three fringing control sites at a depth of 50' and 70'. Sediments were collected using an air-lifted suction device (Figure 3) which was powered by a SCUBA cylinder. A core was first embedded in the sediment enclosing an area of 45cm diameter. The airlift was then used to suction the core to a depth of 10cm into a 1mm mesh bag. Two cores, side-by-side were collected to form a single sample. Five replicate samples were collected from each location during each survey and taken back to shore for sieving in a 2mm mesh before sorting.

Figure 3: *Diver-operated apparatus used for sampling Lagoon infauna. The sampler employed the same principles for lifting samples of sediment as the dredger itself.*



Ciguatera

The abundance of *Gambierdiscus toxicus* (the microalga responsible for ciguatera) was sampled using a method similar to Yasumoto *et al.* (1980a,b). This is a simple washing procedure to separate dinoflagellate from host seaweed. Weighed samples of approximately 100g of the alga *Dictyota* cf *acutiloba* were placed in a plastic container to which filtered seawater was added. The contents of the container were then shaken vigorously for 2 minutes (~250 shakes) before being sieved at 1 mm and 38 microns. The residue on the 38 micron sieve was then washed into a 50 ml vial to which 5 ml of concentrated formalin had been added. Samples were brought back to the laboratory (in Australia), quickly shaken to resuspend particles, and allowed to settle for several days. After settlement, each vial was found to contain a basal sediment layer, a layer of partially suspended mainly organic matter and an uppermost layer consisting of transparent formalin and seawater solution. Neither the formalin solution nor the sedimentary layer were found to contain *G. toxicus* that would have been alive at the time of collection (there were some skeletons in the sedimentary layer).

To estimate the abundance of *G. toxicus* in a sample, the thickness of the primarily organic layer was measured in the pre-settled but undisturbed sample jar using vernier callipers (correct to 0.1 mm) for later determination of volume. Five replicate 0.1 ml subsamples of the organic layer were drawn from each jar using a micro-pipette and mounted individually on a microscope slide. All cells of *G. toxicus* present on each slide were counted for the 5 replicates and the volume measurement was used to obtain an estimate of the total number of cells present in the organic layer of the sample (and hence the whole jar). This value gave abundances of cells per 100g of host alga (note the estimate was adjusted accordingly if more or less than 100g of the original host seaweed had been collected).

2.2.4 Analysis of data

For the purposes of this preliminary report, data were analysed visually from graphs of mean density or percent cover calculated for all sites except the impact grid from Surveys 1 to 4. All means are accompanied by plots of standard errors to facilitate interpretation. Formal analysis of the entire data set will be included in the Final Report when Surveys 5 and 6 have been completed. Here we only present data for the reef top and slope habitats, including fish, corals, algae, mobile invertebrates and *G. toxicus*.

2.3 Results

2.3.1 Pre-existing conditions: Comparisons among dredge and control sites prior to dredging

Fish

The fish assemblages associated with the fringing coral reef exhibited substantial differences between dredge impact sites (D and VR) and controls (SC, NC1, NC2 and LR) prior to the commencement of dredging activities (Table 3). Several wrasse species were found in greater numbers at future dredge site D, including *Cheilinus trilobatum* (Figure 4), *Halichoeres margaritaceous* (Figure 6), *Halichoeres trimaculatus* (Figure 7), *Stethojulis bandanensis* (Figure 8) and *Thalassoma amblycephalum* (Figure 9). In contrast, the birdnose wrasse *Gomphosis varius* (Figure 5) and *Thalassoma hardwicki* (Figure 10) were more abundant at control sites. The wrasse *Thalassoma quinquivittatum* was the only common wrasse species found at station D at similar densities to the controls (Figure 11). The other future impact site, Vaiaku Reef (VR) was generally more similar to the controls, although supported higher densities of *Cheilinus trilobatum* (Figure 4) and *Thalassoma quinquivittatum* (Figure 11) in the reef top habitat.

Pre-existing differences also occurred for the other indicator fish taxa. The density of the surgeonfish *Ctenochaetus striatus* was marginally higher on the reef slope at D compared with controls (Figure 14), while the other two common species, *Acanthurus lineatus* (Figure 12) and *Acanthurus triostegus* (Figure 13) did not differ from the controls. All three of these species were found on Vaiaku Reef at similar densities to controls.

Two of the common butterflyfishes, *Chaetodon auriga* (Figure 15) and *C. citrinellus* (Figure 16) were also higher than controls at future impact site D. In contrast, *C. trifasciatus* (Figure 17) was virtually absent from D, but was a common component of the butterflyfish fauna at nearly all other stations. Vaiaku reef harboured similar densities of these species, with *C. citrinellus* exceeding controls, but only in the reef top habitat.

In terms of total densities and diversity of fish in the three different fish taxa surveyed, pre-existing differences were less clear. Total wrasse densities were higher at D, both on the reef slope and top (Figure 18), but the sites could not be distinguished in terms of overall diversity (Figure 19). Total numbers of surgeonfish were lower at D on the reef top (Figure 20) and their diversity was marginally lower on the slope (Figure 21). Total numbers of butterflyfish were lower at D on the reef slope (Figure 22), but similar to controls in terms of their diversity (Figure 23). In terms of total fish numbers in all three families combined (Figure 24), and overall diversity (Figure 25) no differences were observed. The second potential impact site, VR, supported marginally higher densities of wrasses, surgeonfish, butterflyfish and total densities in the reef top habitat only. The diversity of butterflyfish also tended to be higher at this site.

Table 3: Pre-existing differences in fish between dredge impact sites and controls. 0 = no difference between impact and controls; > = number greater at impact sites than at controls; < = number at impact sites less than at controls.

	Dredge versus Controls		Vaiaku Reef versus Controls	
FISH SPECIES / CATEGORIES	Reef Slope	Reef Top	Reef Slope	Reef Top
WRASSES				
Cheilinus trilobatum	>	>	0	>
Gomphosus varius	<	<	0	0
Halichoeres margaritaceous	>	>	0	0
Halichoeres trimaculatus	>	>	0	0
Stethojulis bandanensis	>	>	0	0
Thalassoma amblycephalum	>	>	0	0
Thalassoma hardwicki	<	<	0	0
Thalassoma quinquivittatum	0	0	0	>
SURGEONFISH				
Acanthurus lineatus	0	0	0	0
Acanthurus triostegus	0	0	0	0
Ctenochaetus striatus	>	0	0	0
BUTTERFLYFISH				
Chaetodon auriga	>	>	0	0
Chaetodon citrinellus	>	>	0	>
Chaetodon trifasciatus	<	0	0	0
GROUPS				
Total wrasses	>	>	0	>
Wrasse diversity	0	0	0	0
Total surgeonfish	0	<	0	>
Surgeonfish diversity	<	0	0	0
Total Butterflyfish	<	0	0	>
Butterflyfish diversity	0	0	0	>
Total fish	0	0	0	0
Total diversity	0	0	0	0

Invertebrates

The large mobile invertebrate fauna on the reef was dominated by holothurians (sea cucumbers) and the coral feeding gastropod *Drupella*. At the future dredge site (D) Holothurian sp. 1 was found in higher densities than controls prior to dredging, both on the reef slope and reef top (Table 4, Figure 26). *Drupella* was very site specific in its occurrence, with no differences among future dredge and control stations (Figure

27). In terms of total densities of all mobile invertebrates, dredge sites were within the range recorded at controls (Figure 28).

Table 4: Pre-existing differences in invertebrates, algae, corals and sand between dredge impact sites and controls. 0 = no difference between impact and controls; > = number greater at impact sites than at controls; < = number at impact sites less than at controls.

	Dredge versus Controls		Vaiaku Reef versus Controls	
SPECIES / CATEGORIES	Reef Slope	Reef Top	Reef Slope	Reef Top
INVERTEBRATES				
Holothurian sp1.	>	>	0	0
Drupella sp.	0	0	0	0
Total invertebrates	0	0	0	0
ALGAE				
Dictyota spp.	>	>	0	0
Padina australis	0	0	0	0
Halimeda opuntia	0	>	0	0
Turf algae	0	0	0	0
Total % algae	>	0	0	0
Algal diversity	>	>	0	0
CORALS				
Staghorn *Acropora* (density)	<	<	0	0
Staghorn *Acropora* (% cover)	<	<	0	0
Plating *Acropora* (density)	0	0	>	>
Pocillopora damicornis (density)	0	0	0	0
Pocillopora verrucosa (density)	0	0	0	0
Total corals (density)	<	<	0	0
Total corals (% cover)	<	<	0	0
Coral diversity	0	0	0	0
Sand	0	>	<	0

Algae

The cover of the dominant algal species tended to be higher at the dredge site (D) compared with the controls (SC, NC1, NC2 and LR) prior to the dredging operations (Table 4). *Dictyota* sp. accounted for 20-30% of the total benthic cover at D, compared with less than 10% at the controls at the beginning of the study (Figure 29). The cover of *Padina australis* was similar at dredge and control stations (Figure 30), whereas *Halimeda opuntia* was higher at D on the reef top, compared with this habitat at controls (Figure. 31). The cover of turfing algae at the dredge site was in the range of the controls (Figure 32), but the total cover of all algal species combined (Figure 33) was higher than the controls for the reef slope habitat. The diversity of algae was substantially higher (almost twice the number of species per unit area) at the dredge site, for both reef slope and reef top habitats (Figure 34).

Prior to dredging, measures of algal cover and diversity at the second impact site, Vaiaku Reef (VR), were in the range found at the controls (Figures 28-33).

Corals

In contrast to algae, coral cover tended to be lower than the controls at the primary dredge site, and in some cases the difference was extreme (Table 4). Staghorn Acroporids were poorly represented at station D (< 5 individuals per transect), but were in the range of 10-50 individuals per transect at control sites (Figure 35). Staghorns did not even register in terms of percent cover at D, but reached 60% at some of the control sites (Figure 36). In contrast, plating Acroporids (Figure 37), *Pocillopora damicornis* (Figure 38) and *P. verrucosa* (Figure 39) were found at similar densities to controls. The total densities of all coral species combined were lowest at D (less than half the density of the nearest control site, Figure 40). Where total percent cover of all corals combined reached 70-80% on the reef slope at some of the controls (SC and LR), the future dredge impact site was already less the 5% coral cover (Figure 41). At this site there was virtually no coral on the reef top. High levels of coral cover on the reef top were only observed at one of the control sites (LR). In terms of coral diversity (mean number of species per transect), the dredge site was well within the range observed at the controls (Figure 42).

The reef adjacent to the future dredge site (VR) was similar to the controls in terms of overall coral densities, cover and diversity (Table 4, Figures 34-41). The only differences of note were the higher densities of plating corals at VR, both on the reef slope and top (Figure 38).

Sand

The percent cover of sand varied among the stations sampled prior to dredging (Figure 43). In terms of pre-existing differences between dredge and control stations, D exhibited higher cover of sand on the top of the reef (12% at the first sampling date, compared with less than 2% at the controls). VR had extremely low sand accumulation prior to dredging, but was only significantly lower than controls on the reef slope.

2.3.2 Qualitative Observations

No unusual conditions of coral health were observed at any of the census locations during Survey 3.

During Survey 4 we detected impacts on the health of coral communities at Vaiaku Reef, but not at any of the other sites investigated. This reef is a free-standing patch reef located several hundred metres into the lagoon from the Vaiaku Lagi Hotel, and is situated approximately 200m to the north of the dredge line. Soon after arrival on

Trip 4 we surveyed this reef, in keeping with our normal survey design. On 21st June, visibility on Vaiaku Reef was down to 2-3 metres. The sediment load on corals, sponges and the substratum was heavy, up to several millimetres in thickness. The corals themselves were showing stress in three ways: (i) heavy production of mucus sheets which were rolling off the corals with water movements; (ii) bleaching of coral colonies (especially plating corals in the Genus *Acropora*); (iii) partial mortality (minor) of some coral colonies. Although damage was obvious we judged that further monitoring should take place before action on dredging operations should be taken. Our previous experience with larger-scale dredging operations suggested that widespread permanent damage to the reefs would not occur immediately - most corals can recover from all three forms of damage (mucus, bleaching and partial mortality) if the stressing pressures are relieved. We had noted that the damage to corals occurred after several days of SE winds which would have brought dredging sediments directly in line with the reef in question.

We re-scanned the reef at intervals throughout our trip up until 11th July. By that date the winds had swung more to the East and the clarity of waters on Vaiaku Reef had increased back to normal levels (10 m+). At that time, we re-examined the reef community and found that much of the sediment film covering corals and the substratum had disappeared. The abnormally heavy mucus production had diminished, and those corals which had been bleached were showing signs of recovery. The few corals that had suffered some partial mortality did not recover.

2.3.3 Quantitative Surveys: Impact of dredging - Comparisons between "before" and "during" surveys

Fish

Dredging appeared to have an effect on the abundance of some of the fish species surveyed, with both increases and decreases relative to controls being recorded (Table 5). Among the wrasses, *Halichoeres margaritaceous* increased on the reef tops of D and VR, with no significant trends occurring at the controls (Figure 6). For *H. trimaculatus*, a significant trend toward an increase at D was reversed during the dredging period on both the reef slope and top (Figure 7). A similar trend for this species occurred on the reef top at VR. *Stethojulis bandanensis* underwent an increase in abundance at D during the dredging period, whereas it either declined or did not change at the control sites and VR (Figure 8). *Thalassoma amblycephalum* generally declined between the before and during surveys, but at dredging site D the decline was greatest (Figure 9). Four other wrasses exhibited no temporal changes that were attributable to dredging (*Cheilinus trilobatum*, Figure 4; *Gomphosis varius* Figure 5, *Thalassoma hardwicki*, Figure 10; and *T. quinquivittatum*, Figure 11).

Surgeonfishes exhibited few detectable responses to dredging, although *Acanthurus lineatus* underwent a substantial decline in numbers at Vaiaku Reef that was not observed at the control sites (Figure 12). Among the butterflyfish, the density of *Chaetodon citrinellus* declined at dredge sites D and VR, but on average remained steady at control sites (Figure 16). *Chaetodon trifasciatus* declined on reef slopes at all study sites, but proportionally greater declines occurred at Vaiaku Reef (Figure 17).

Overall densities and diversities of all wrasses, surgeonfish and butterflyfish showed no effects attributable to dredging (Figures 17 - 22). Butterflyfish abundance and diversity exhibited a decline between "before" and "during" surveys at both dredge impact and control sites. The same was true for total fish densities and the combined diversity of all three indicator families, which showed minimal change over the four sampling times.

NOTE about Figures 4 to 44. The figures that follow present for each species or variable examined, the abundance or percent cover of that organism. Values are averages +/- Standard Errors presented for the Reef Slope and Reef Top of the two pricipal impact sites and controls included in this study. Data are included for only a subset of species and habitats examined. Locations are: SC = South Control at Muli Malai; D = Dredge site at Vaiaku Wharf; NC1 = North Control 1 at Pig Farm; NC2 = North Control 2 at the Hideaway Lodge; VR = Vaiaku Reef; and LR = Lakau Reef.

FAMILY LABRIDAE - WRASSES - KIOLE

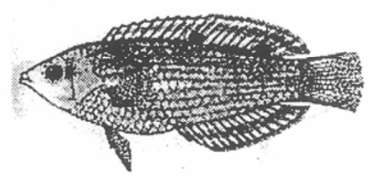


Figure 4: *Cheilinus trilobatum*

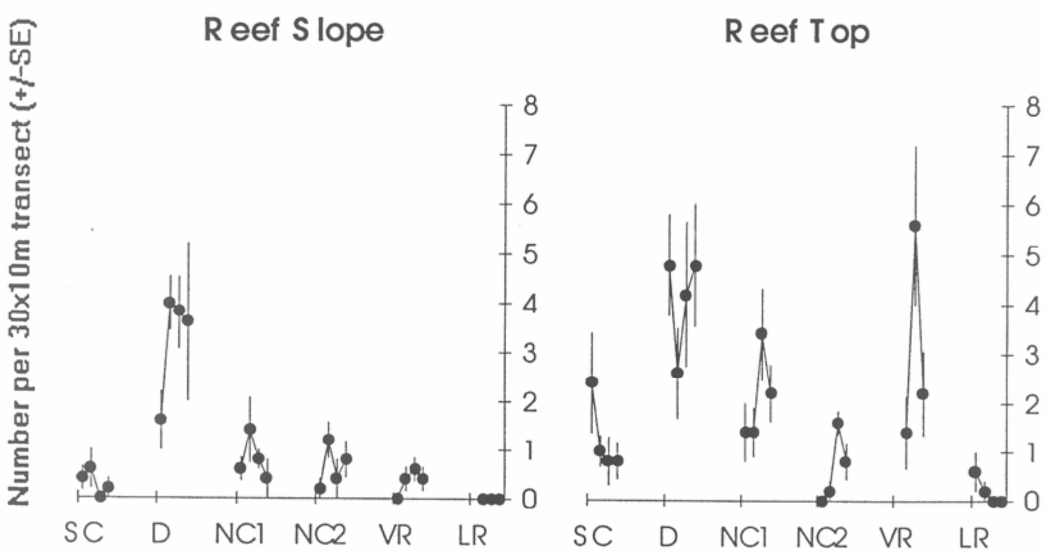


Figure 5: *Gomphosus varius*

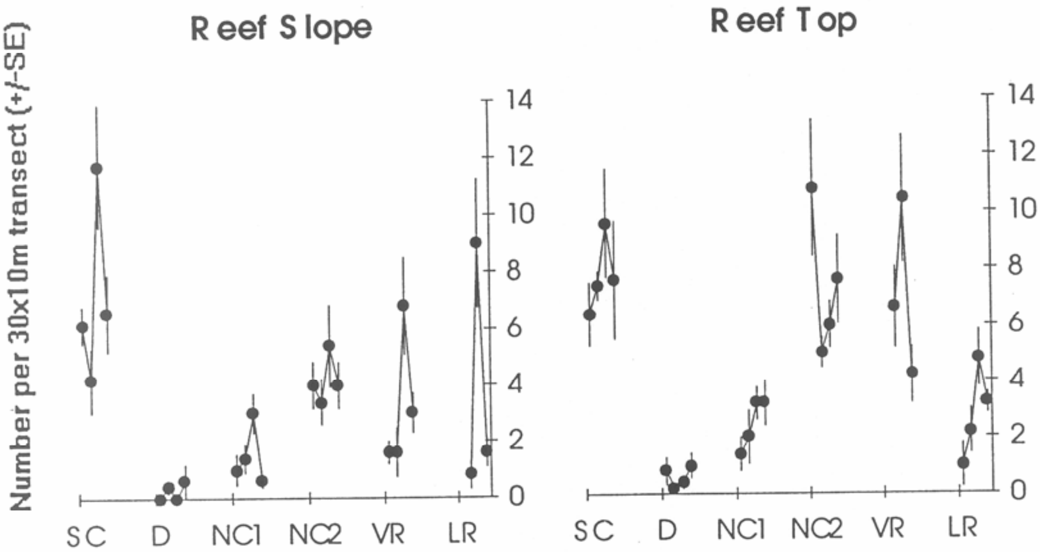


Figure 6: *Halichoeres margaritaceous*

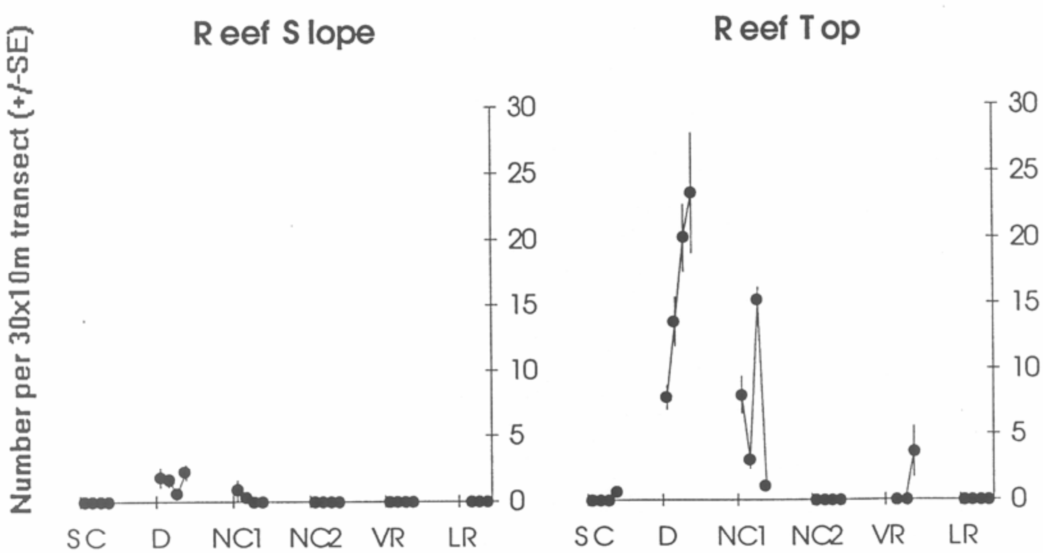


Figure 7: *Halichoeres trimaculatus*

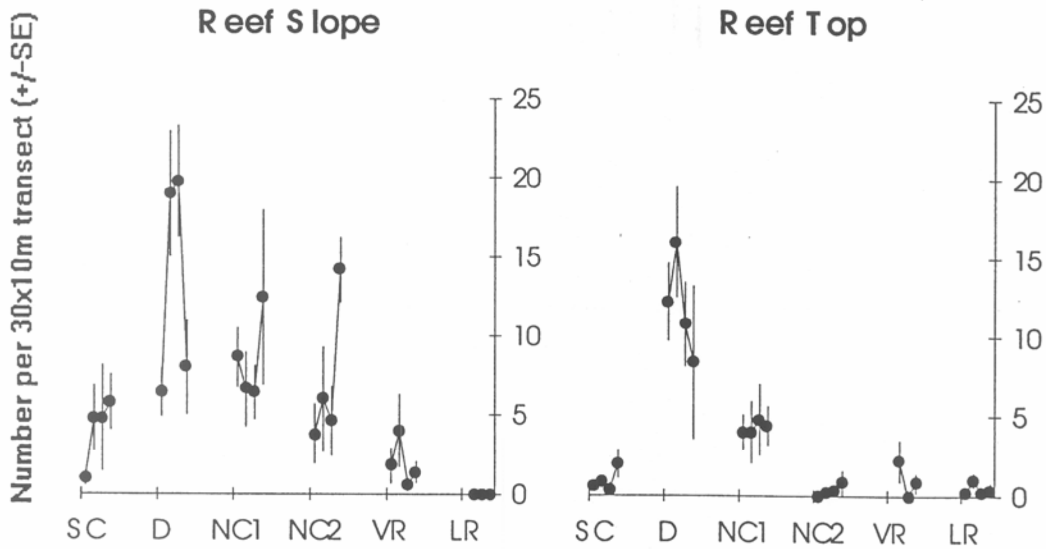


Figure 8: *Stethojulis bandanensis*

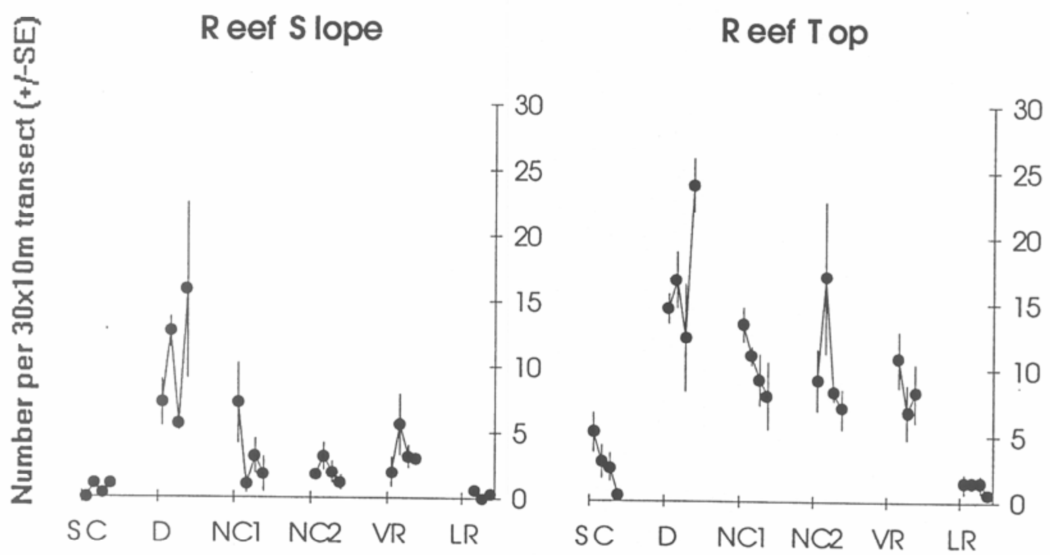


Figure 9: *Thalassoma amblycephalum*

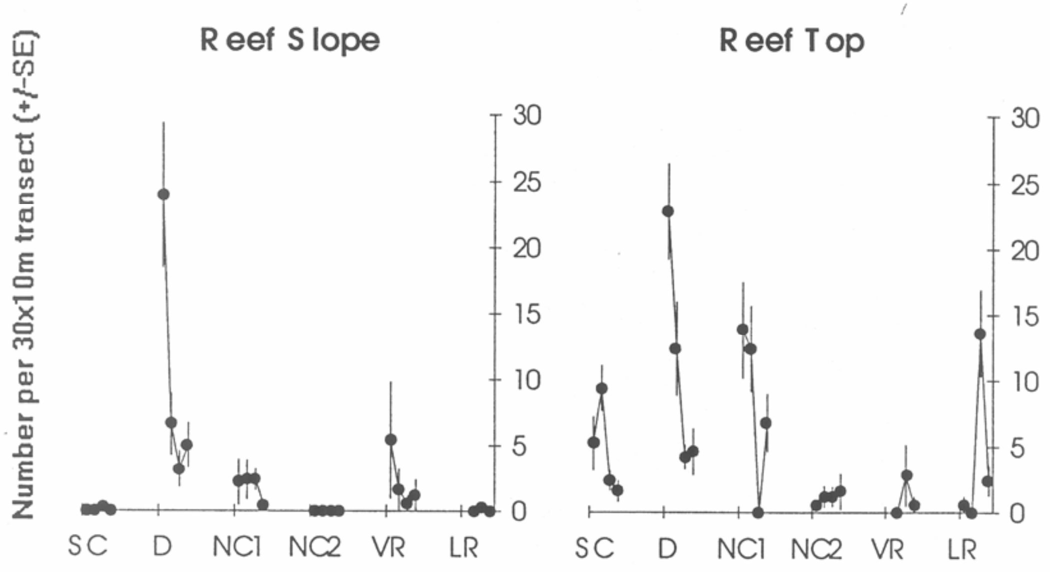


Figure 10: *Thalassoma hardwicki*

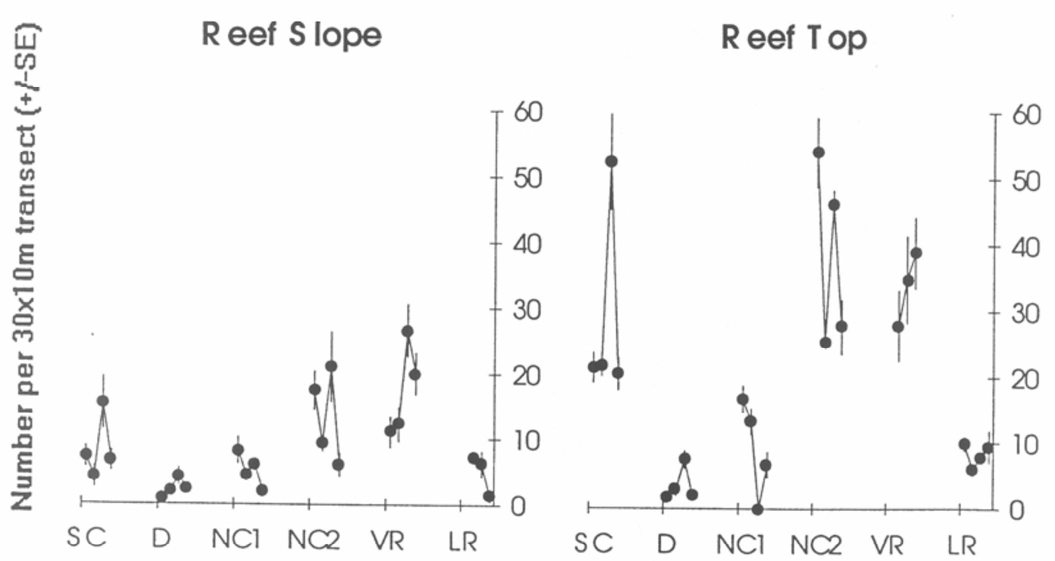
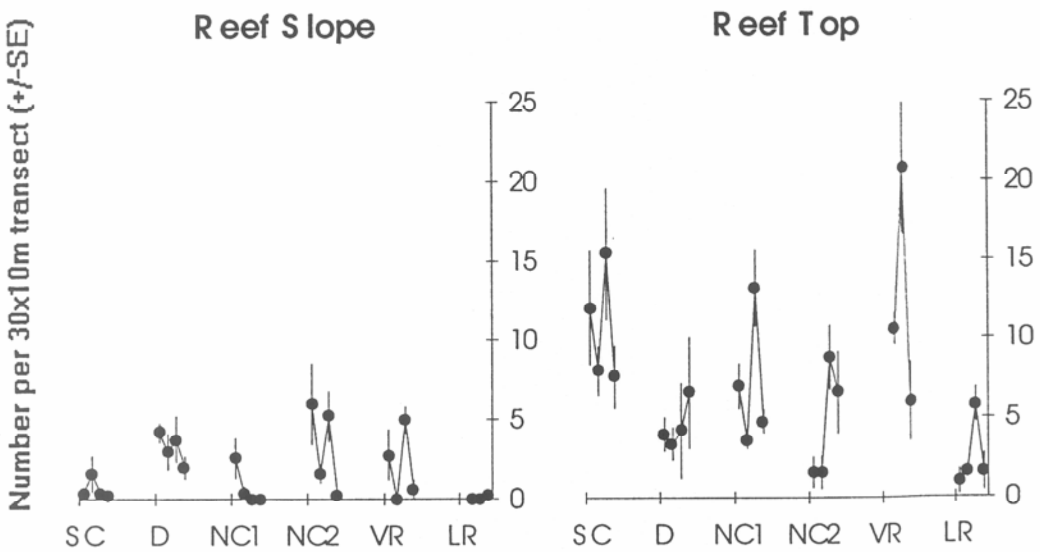


Figure 11: *Thalassoma quinquivittatum*



FAMILY ACANTHURIDAE - SURGEONFISHES - PONE

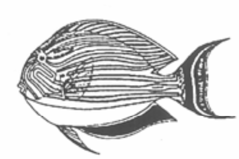


Figure 12: *Acanthurus lineatus*

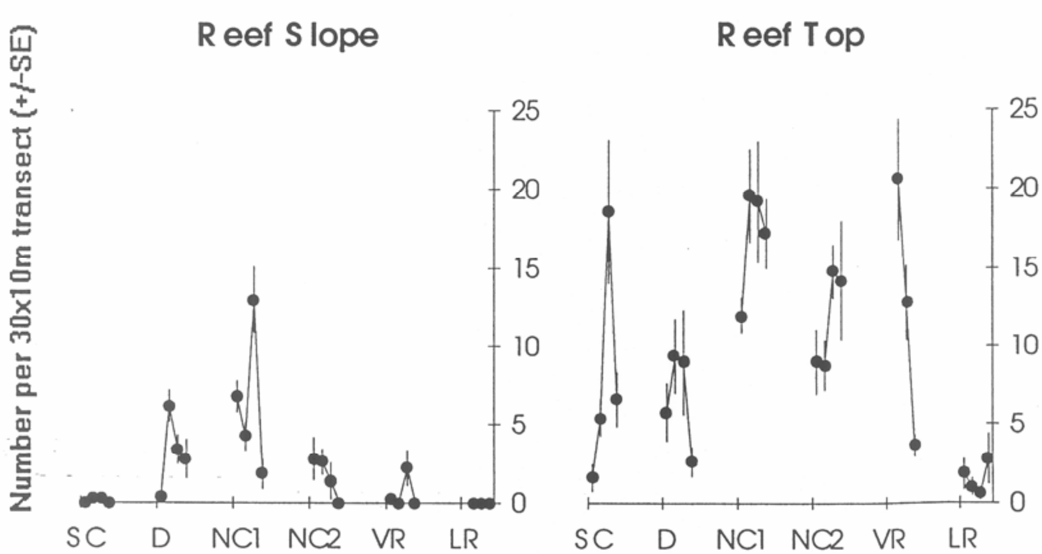


Table 5: Effects of dredging on fish apparent at the "during" dredging phase as differences between impact sites and controls. 0 = no difference between impact and controls; ↑ = increase at impact relative to controls; ↓ = decrease at impact sites relative to controls.

	Dredge versus Controls		Vaiaku Reef versus Controls	
FISH SPECIES / CATEGORIES	Reef Slope	Reef Top	Reef Slope	Reef Top
WRASSES				
Cheilinus trilobatum	0	0	0	0
Gomphosus varius	0	0	0	0
Halichoeres margaritaceous	0	↑	0	↑
Halichoeres trimaculatus	↓	↓	↓	0
Stethojulis bandanensis	↑	↑	0	0
Thalassoma amblycephalum	↓	↓	0	0
Thalassoma hardwicki	0	0	0	0
Thalassoma quinquivittatum	0	0	0	0
SURGEONFISH				
Acanthurus lineatus	0	0	0	↓
Acanthurus triostegus	0	0	0	0
Ctenochaetus striatus	0	0	0	0
BUTTERFLYFISH				
Chaetodon auriga	0	0	0	0
Chaetodon citrinellus	↓	↓	0	↓
Chaetodon trifasciatus	0	0	↓	↓
GROUPS				
Total wrasses	0	0	0	0
Wrasse diversity	0	0	0	0
Total surgeonfish	0	0	0	0
Surgeonfish diversity	0	0	0	0
Total Butterflyfish	0	0	0	0
Butterflyfish diversity	0	0	0	0
Total fish	0	0	0	0
Total diversity	0	0	0	0

Figure 13: *Acanthurus triostegus*

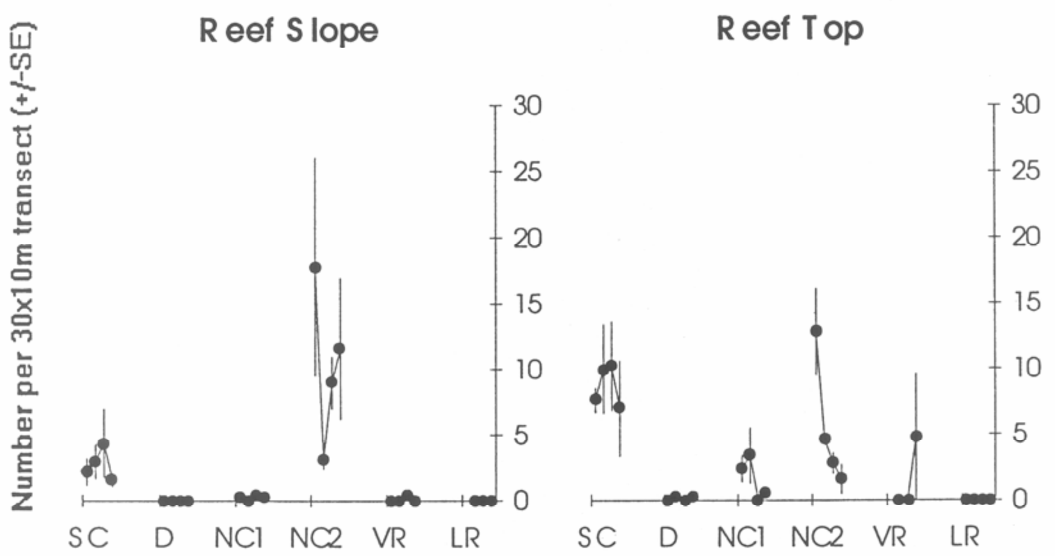
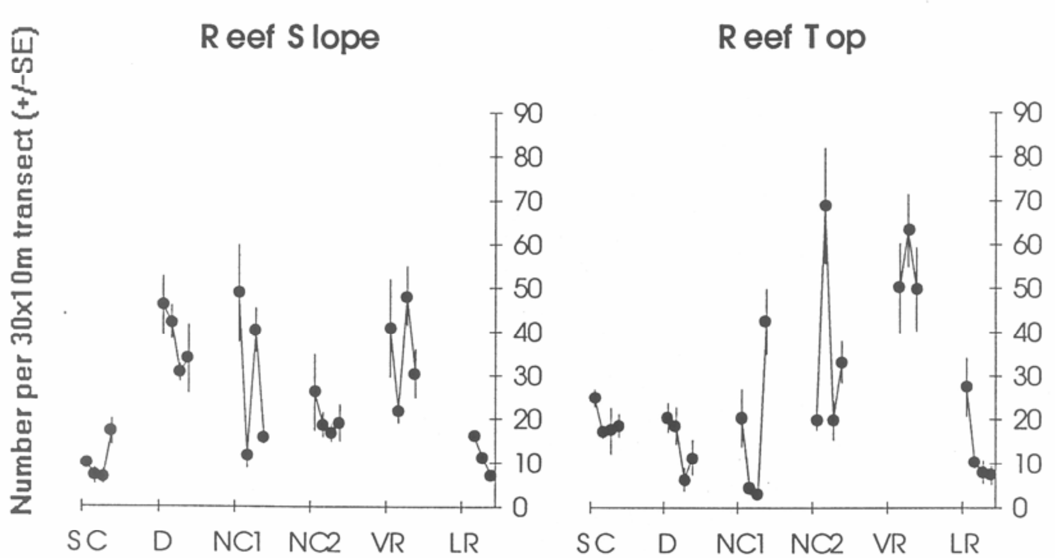


Figure 14: *Ctenochaetus striatus*



FAMILY CHAETODONTIDE - BUTTERFLYFISHES - MOEPEPE

Figure 15: *Chaetodon auriga*

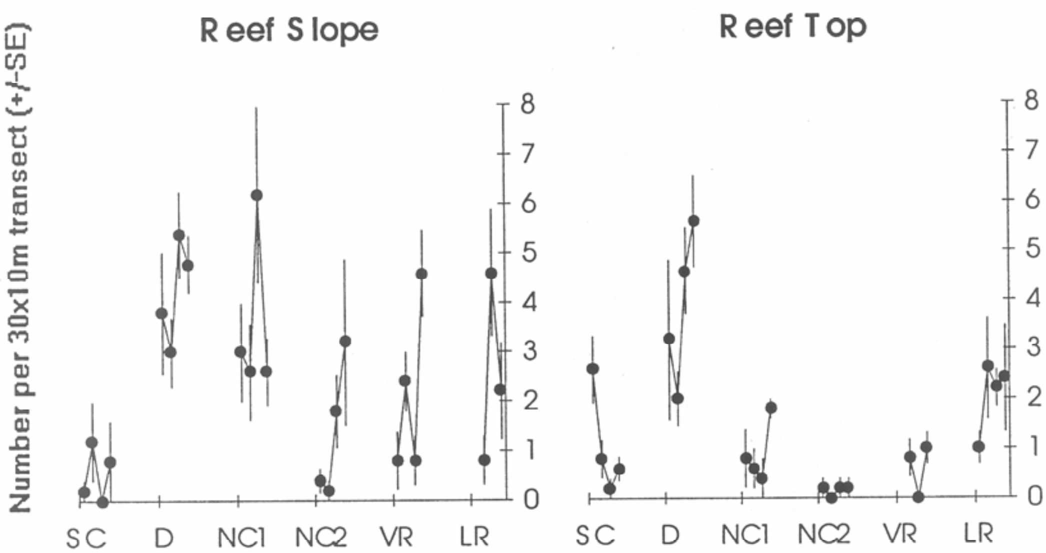


Figure 16: *Chaetodon citrinellus*

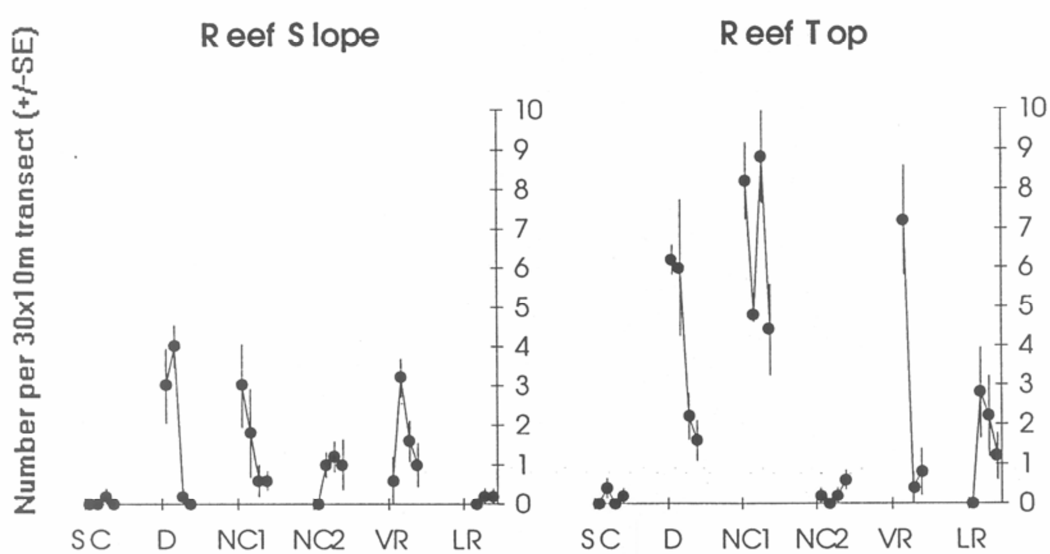
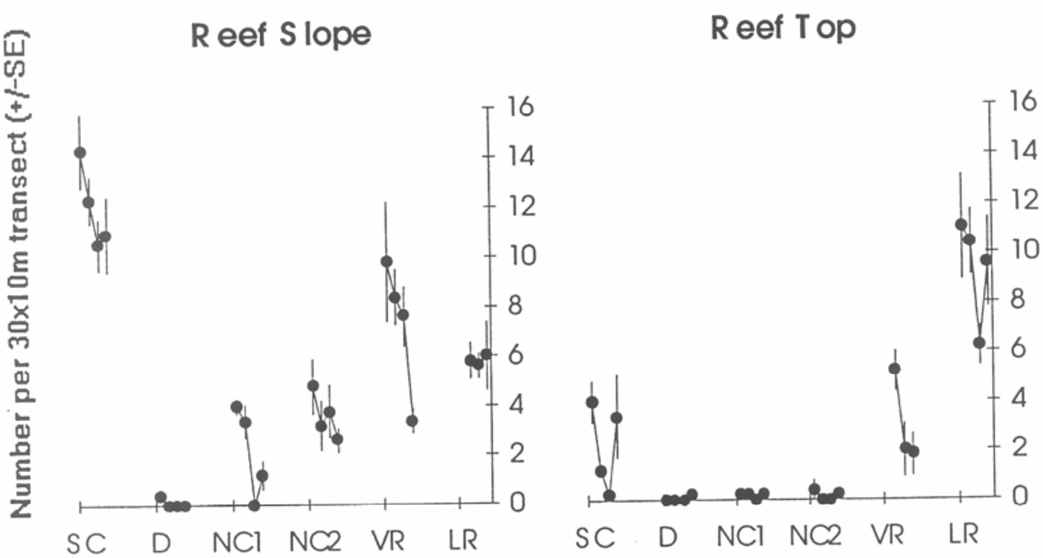


Figure 17: *Chaetodon trifasciatus*



TOTALS FOR FISHES

Figure 18: *Total wrasses*

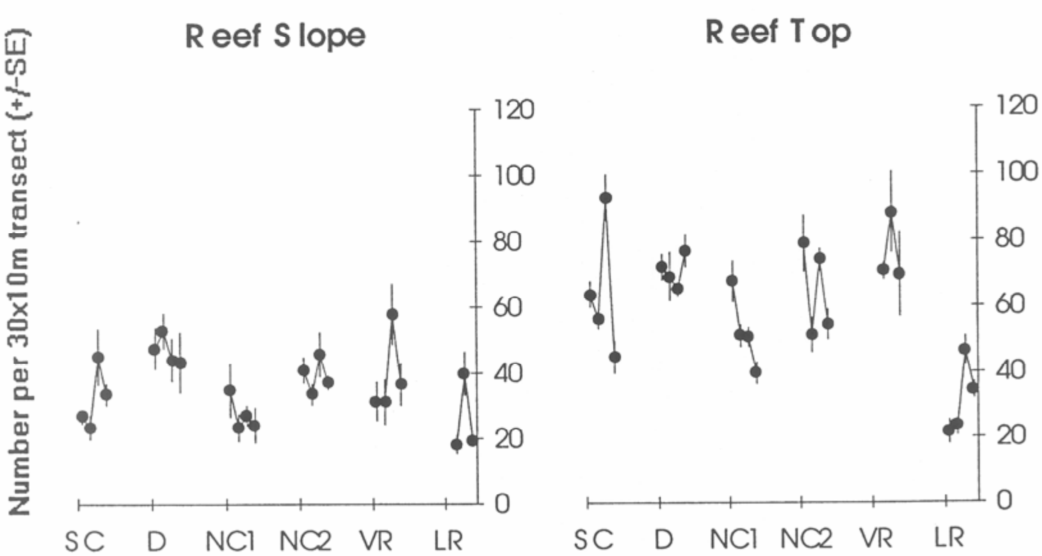


Figure 19: *Diversity wrasses*

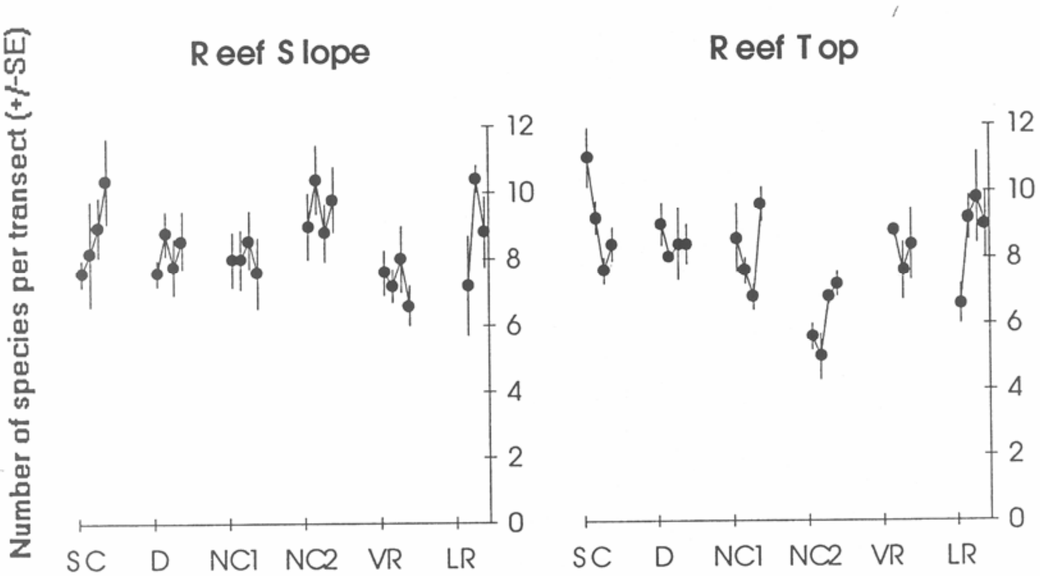


Figure 20: *Total surgeons*

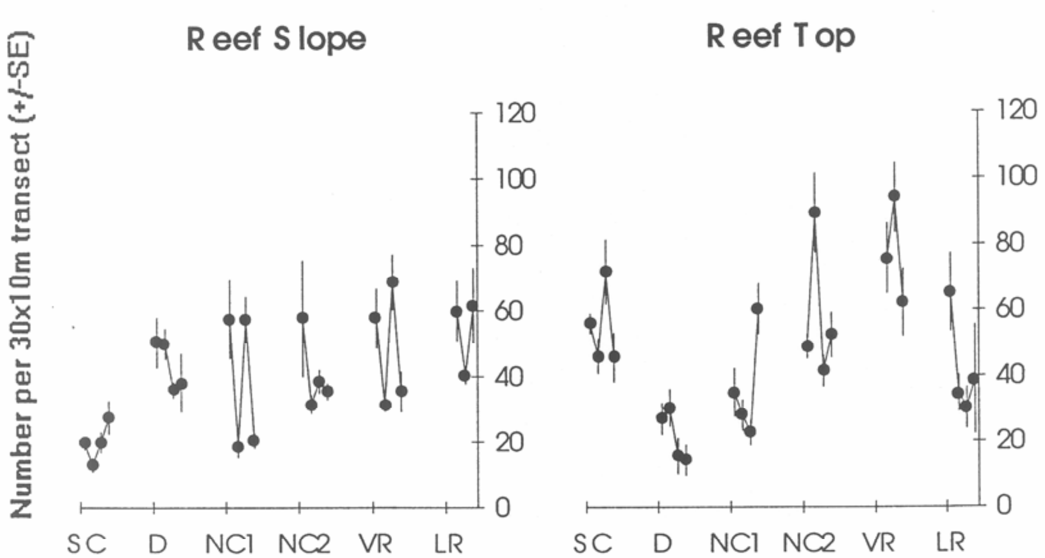


Figure 21: *Diversity surgeons*

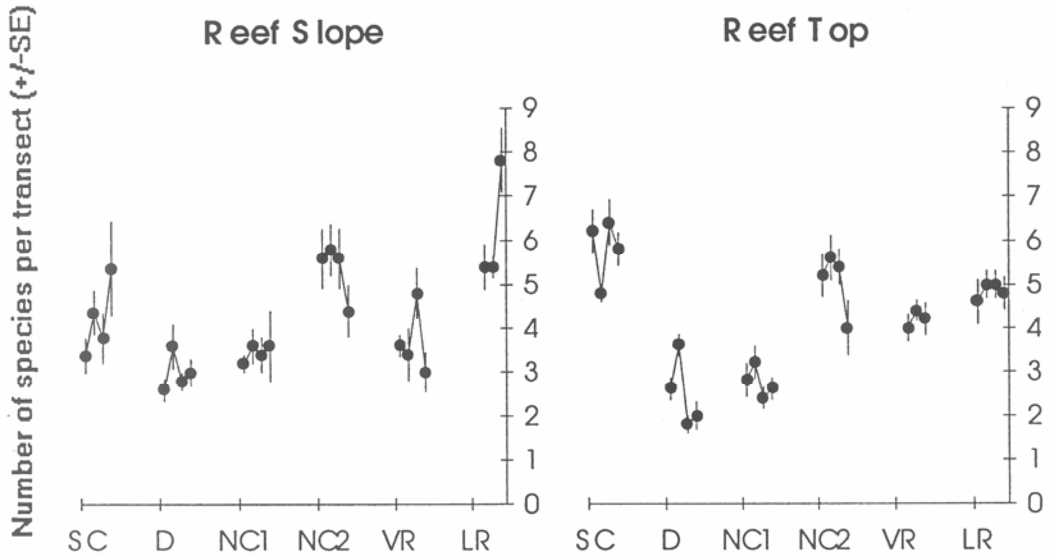


Figure 22: *Total Butterflyfish*

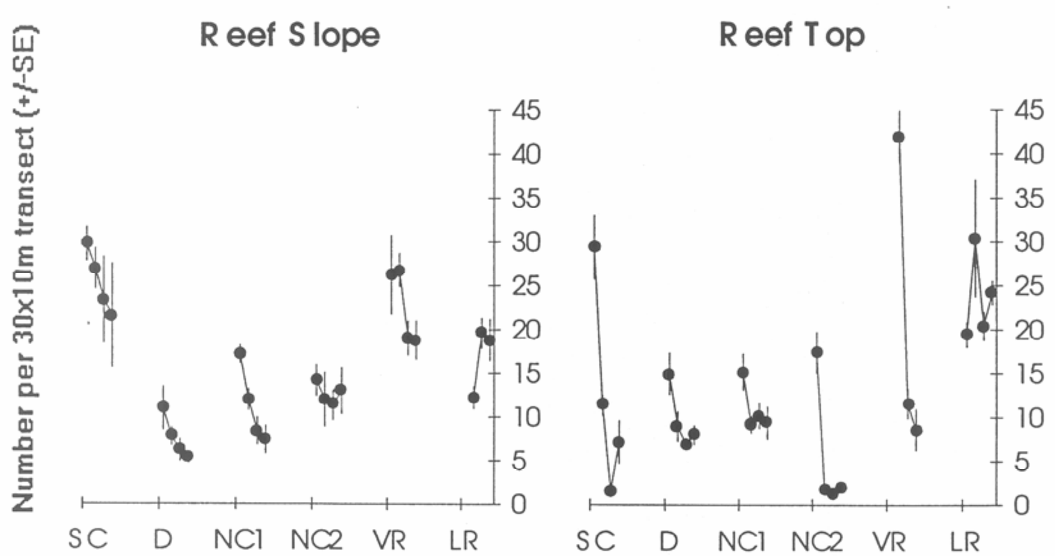


Figure 23: *Diversity Butterflyfish*

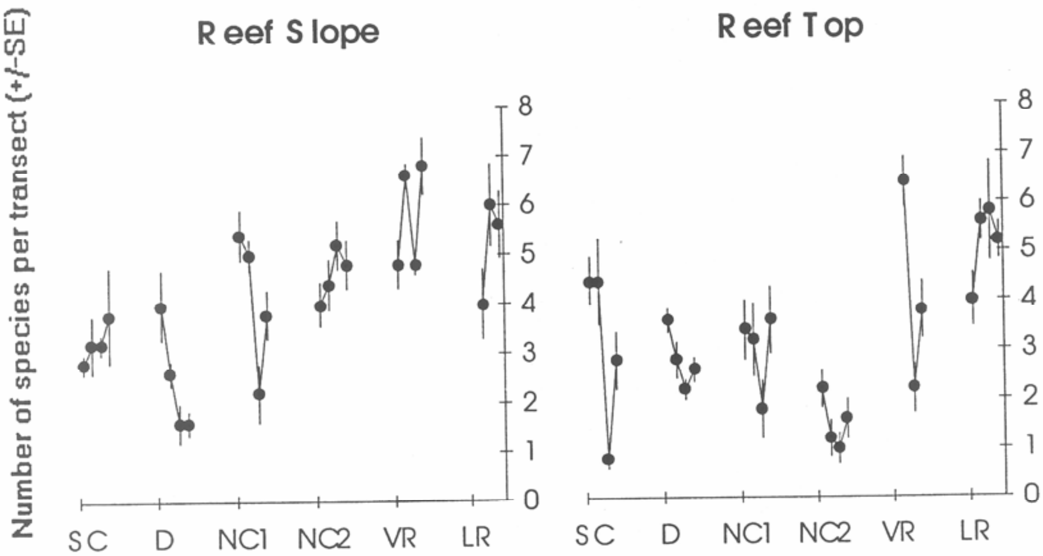


Figure 24: *Total fish (wrasses, surgeonfish & butterflyfish)*

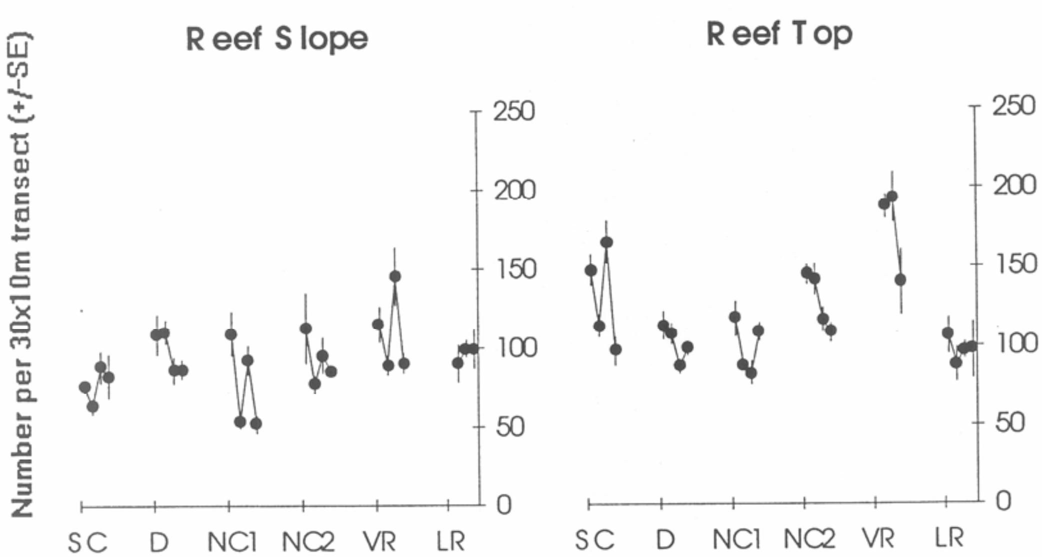
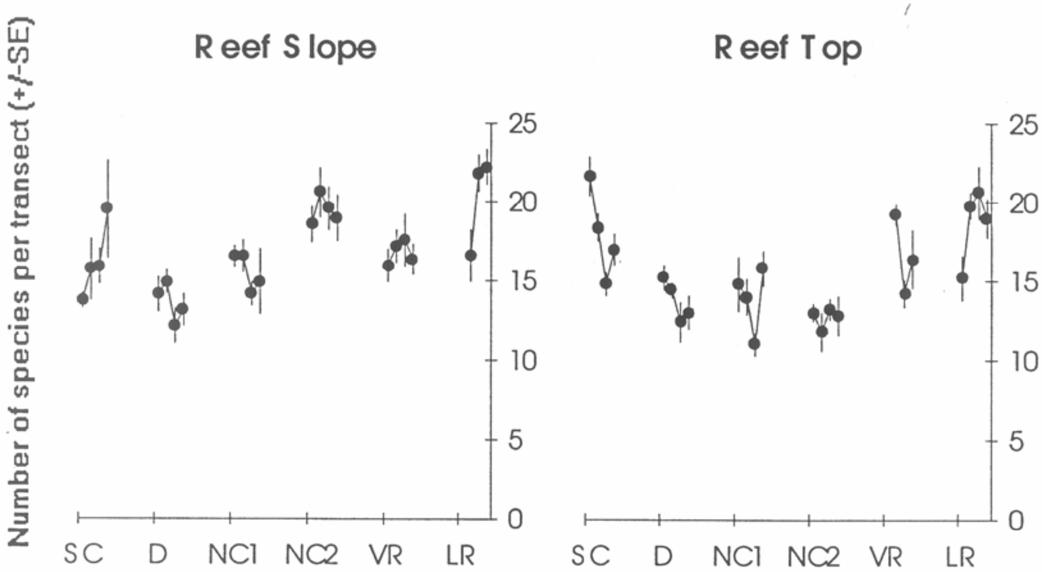


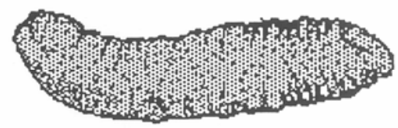
Figure 25: *Diversity (wrasses, surgeonfish & butterflyfish)*



Invertebrates

The density of *Holothurian* sp. 1 (Table 6, Figure 26) and total invertebrate density (Figure 28) underwent an increase at the primary dredge site (D) after dredging commenced. Parallel increases were not observed at the controls or Vaiaku Reef.

Figure 26: *Holothurian sp1*



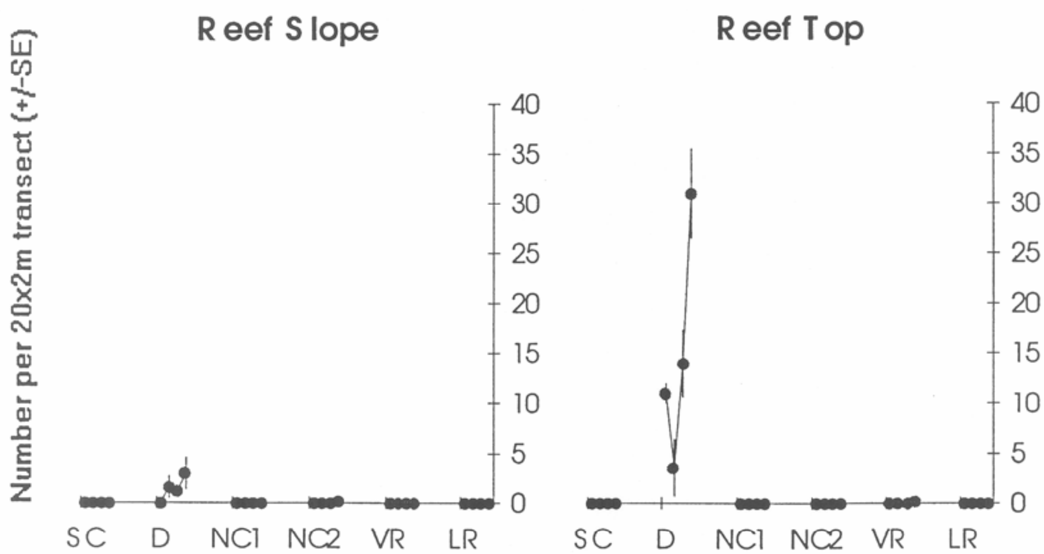


Figure 27: *Drupella* sp.

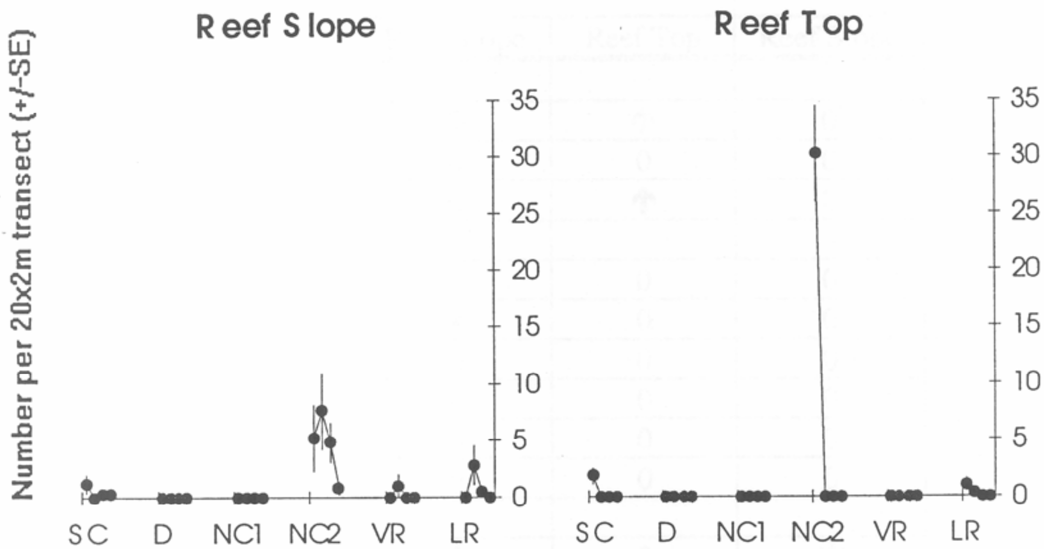
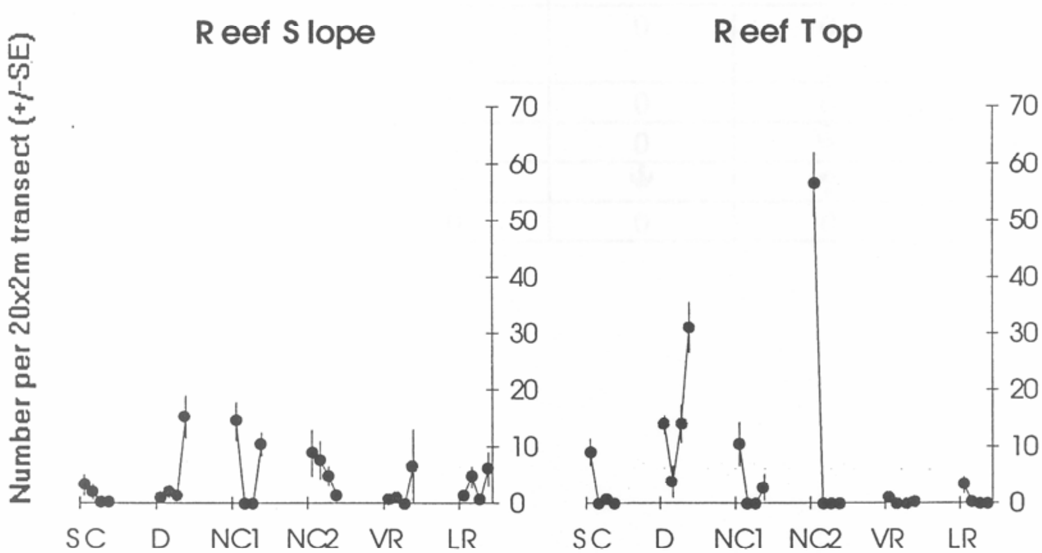


Figure 28: *Total invertebrates*



Algae

Dredging had an effect of increasing the cover of two algal species at the primary dredge site (D) (Table 6). The cover of *Dictyota* sp. increased on the reef slope at D, but did not change at the other stations (Figure 29). Major increases were also observed at D and VR on the reef top, but this also occurred at 2 of the 4 control sites. A marked increase in *Padina australis* occurred at dredge site D on the reef slope, an increase that was greater than at any of the controls. For other algal categories, including *Halimeda opuntia*, turfing algae, total % cover algae and algal diversity, no effects of dredging were detected. There was a general trend toward an increase in algal cover at the majority of the sites examined.

ALGAE - LIMU

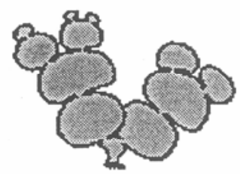


Figure 29: *Dictyota sp.*

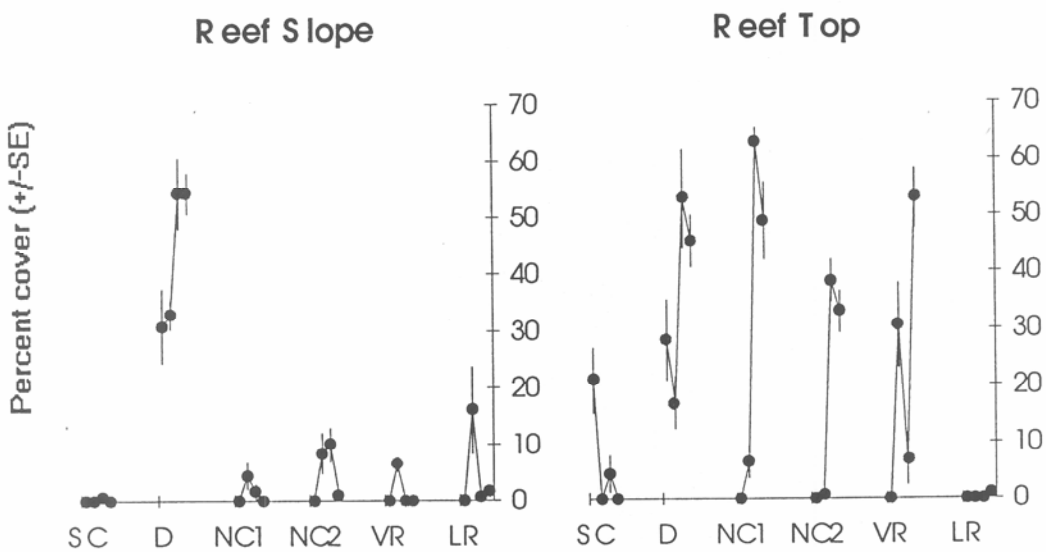


Figure 30: ***Padina australis***

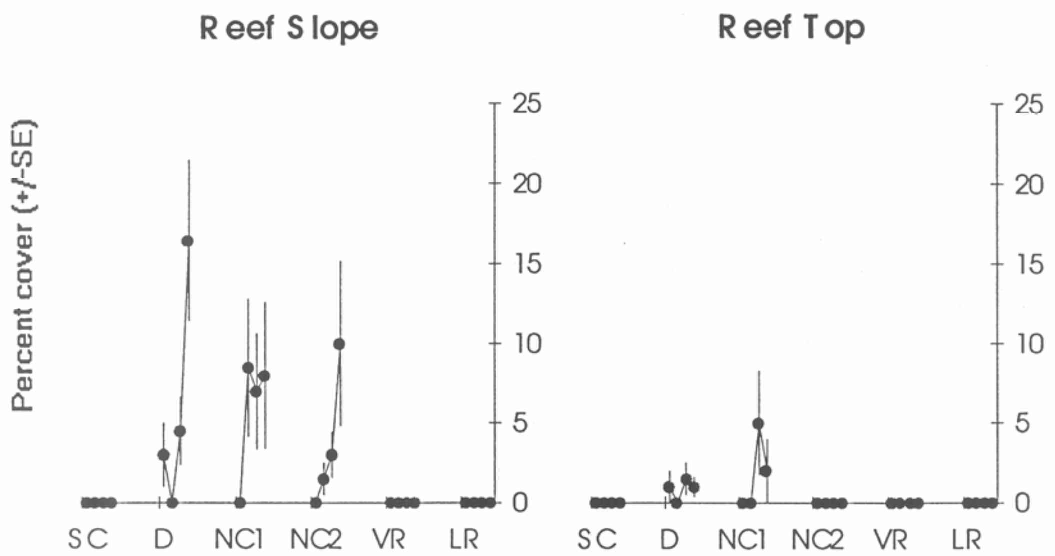


Figure 31: *Halimeda opuntia*

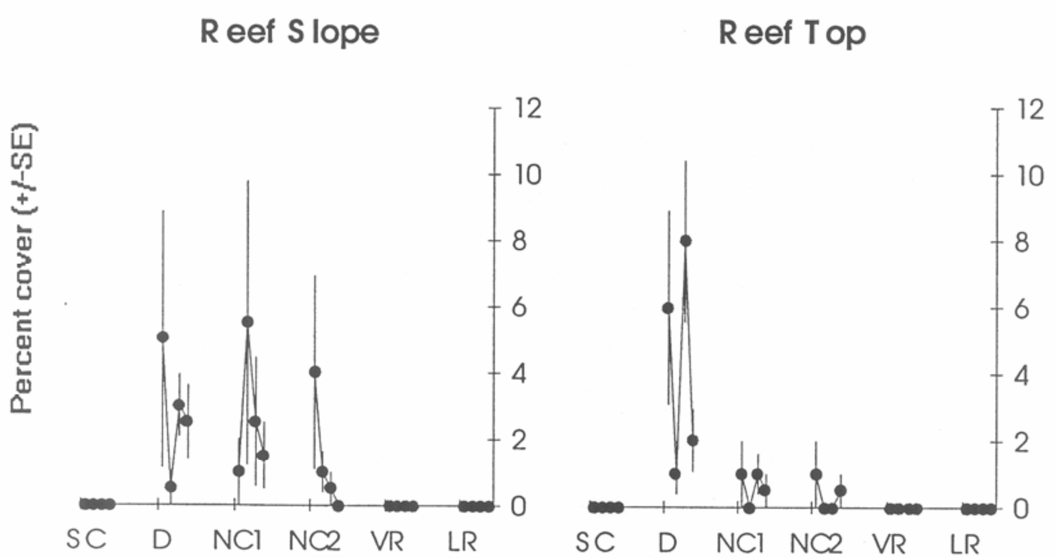


Figure 32: *Turfing algae*

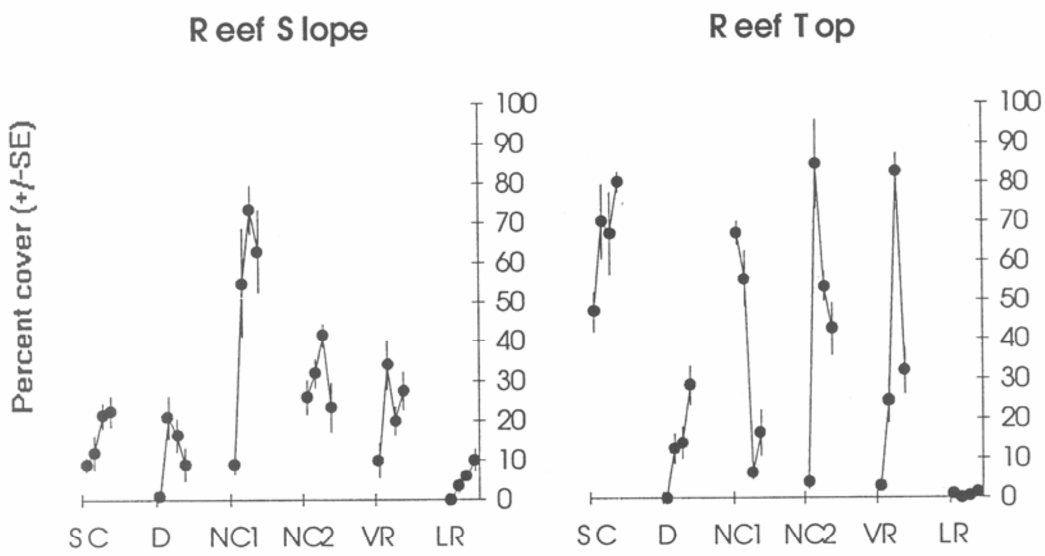


Figure 33: *Total % algae*

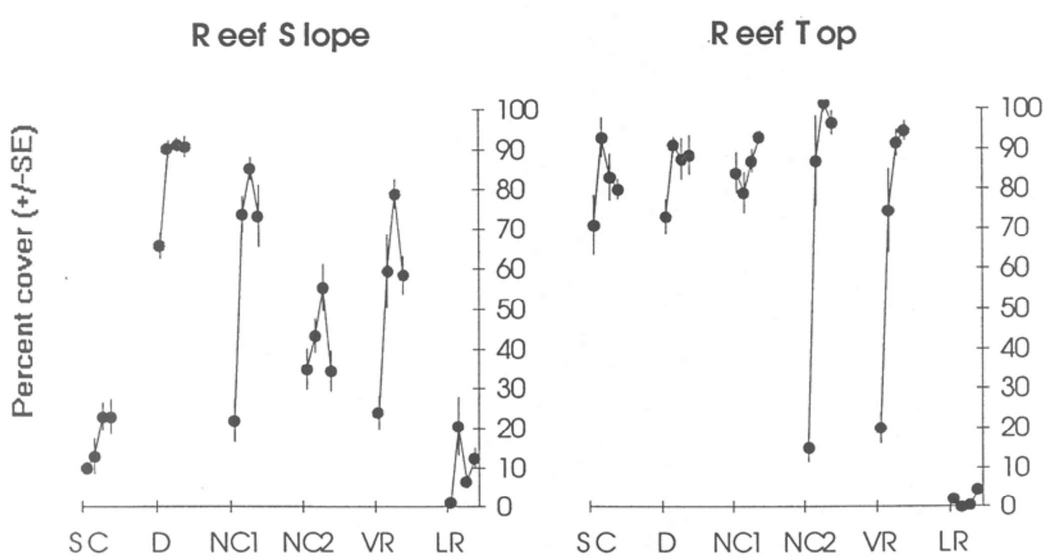
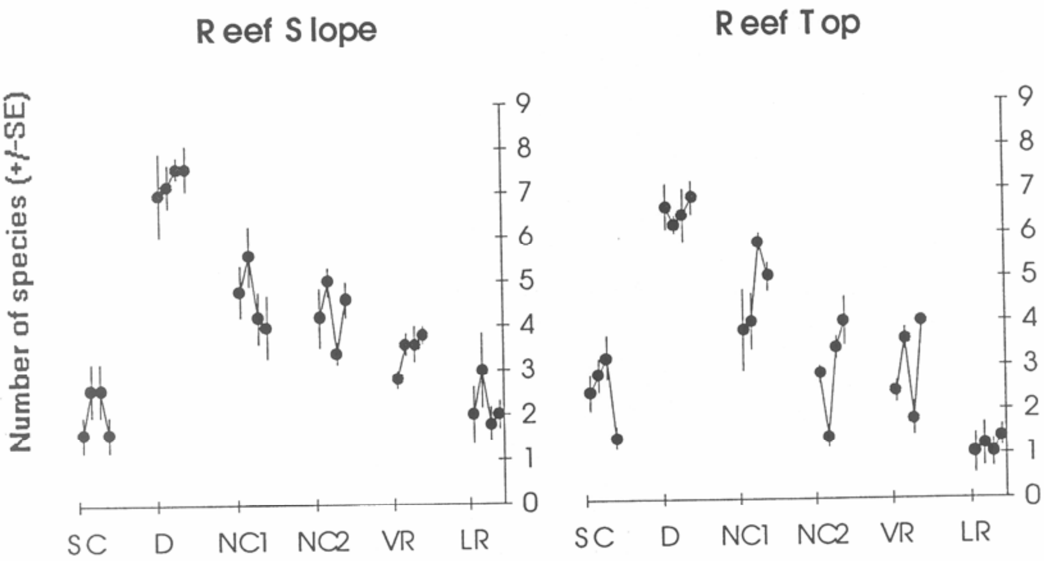


Figure 34: *Diversity algae*



Corals

Dredging appeared to cause a decline in some coral types, primarily at Vaiaku Reef (Table 6). Staghorn *Acropora* declined at VR on the reef slope, while remaining low and fairly constant at D and tending to show an increase in this habitat at most controls (Figure 35). On the reef top, major declines in staghorn density occurred at Vaiaku reef and three of the four controls. Percent cover of staghorns underwent a decline on both the reef slope and reef top that was greater than at any of the controls (Figure 36). Dredging appeared to cause a decline in the density of plating *Acropora* at Vaiaku Reef (Figure 37). A decline of this magnitude did not occur at any of the control sites or at dredge site D. *Pocillopora damicornis* declined between the before and during surveys at D, but did not change or increased at all other sites (Figure 38), whereas *P. verrucosa* exhibited little change at any of the sites (Figure 39).

The total number of coral individuals and total percent cover showed evidence of decline that were not specific to dredge sites (Figures 39 & 40). The decline in total percent cover was, however, greatest at Vaiaku Reef. After the beginning of dredging, the diversity of coral types increased on the reef slope at both impact sites (D and VR) and declined on the reef tops (Figure 42). Such changes were also observed at some of the control sites.

CORALS

Figure 35: *Staghorn Acropora (density)*

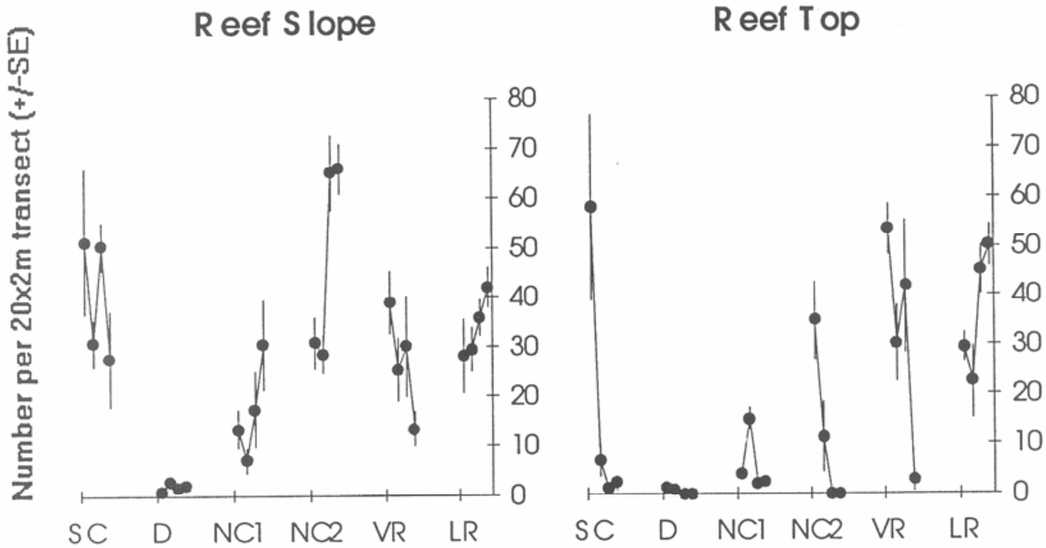


Figure 36: *Percent cover staghorns*

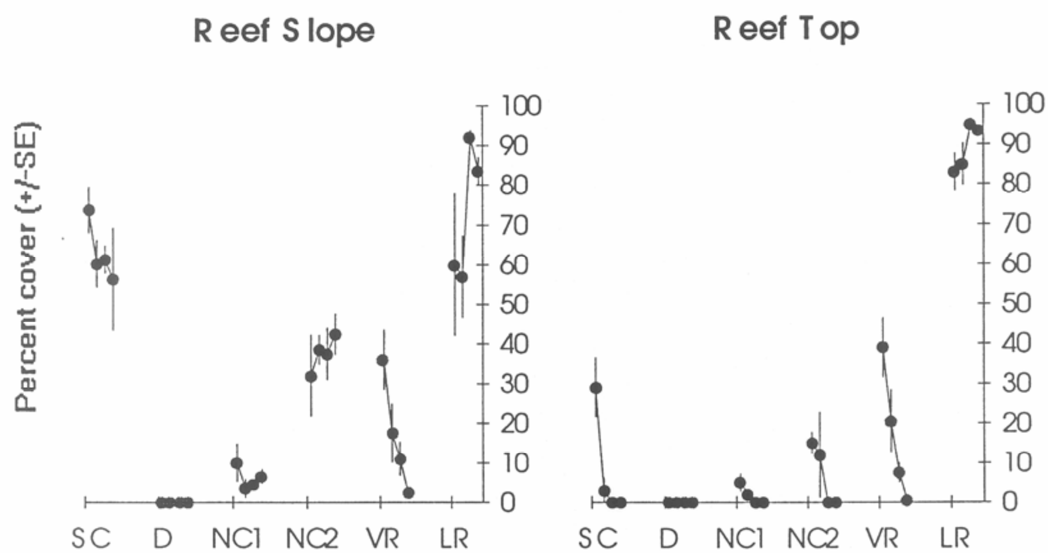


Figure 37: *Plating Acropora (Density)*

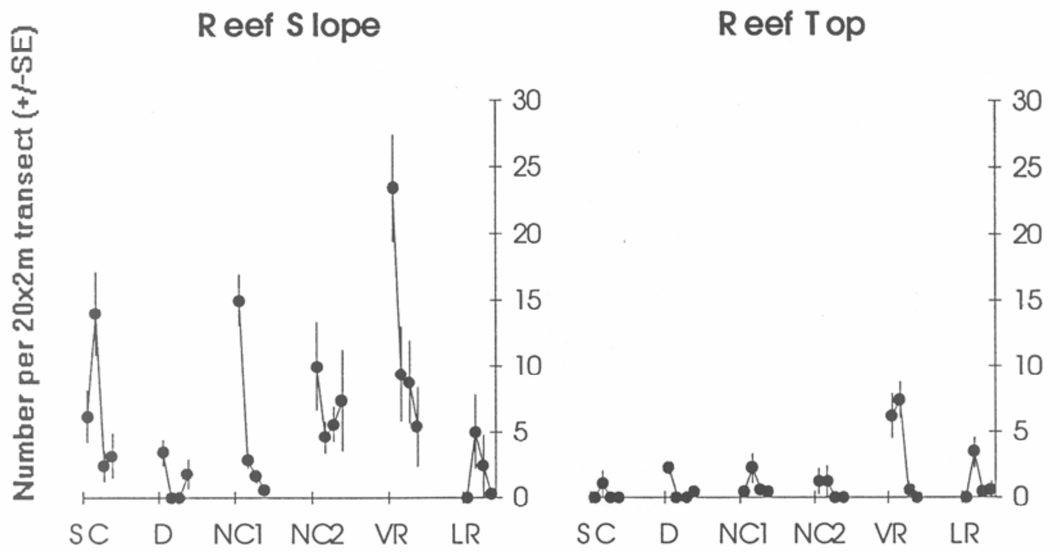


Figure 38: *Pocillopora damicornis (density)*

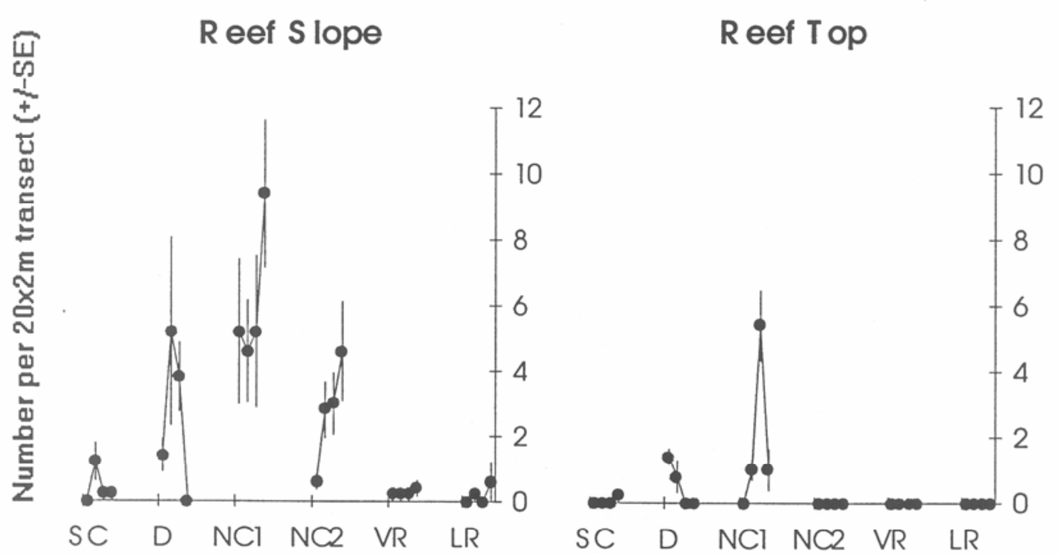
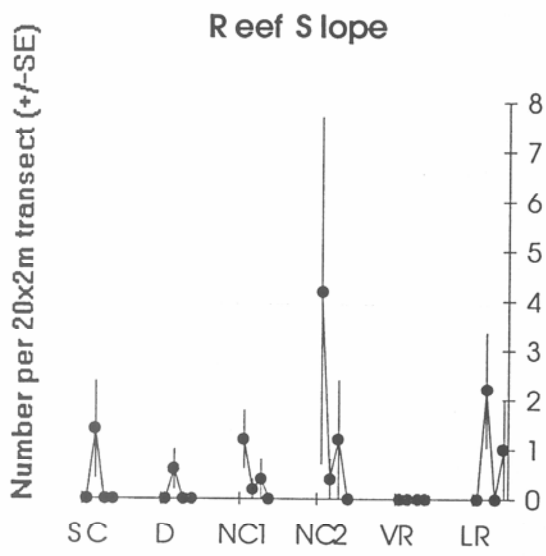


Figure 39: *Pocillopora verrucosa (density)*



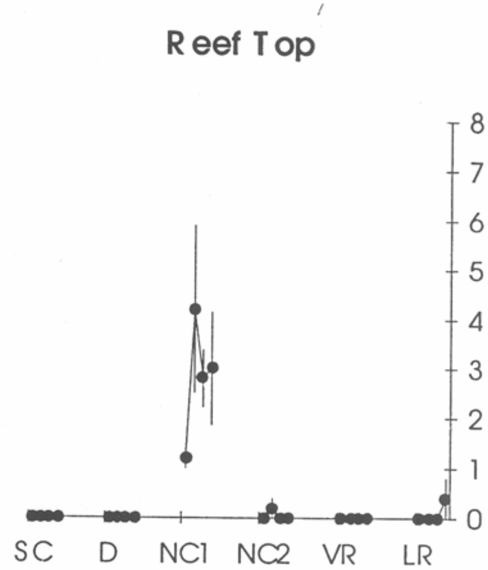
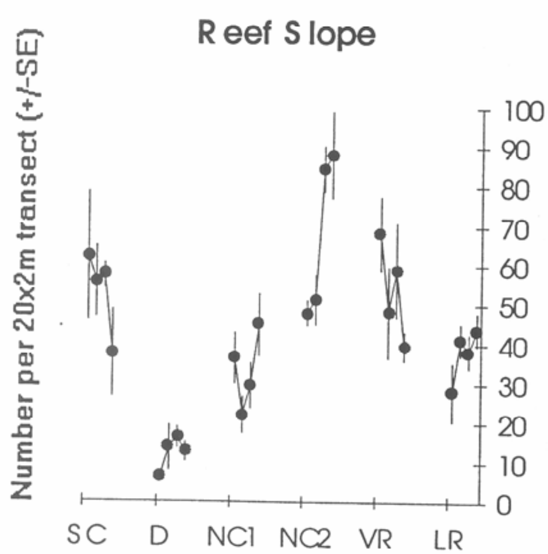


Figure 40: *Total number corals*



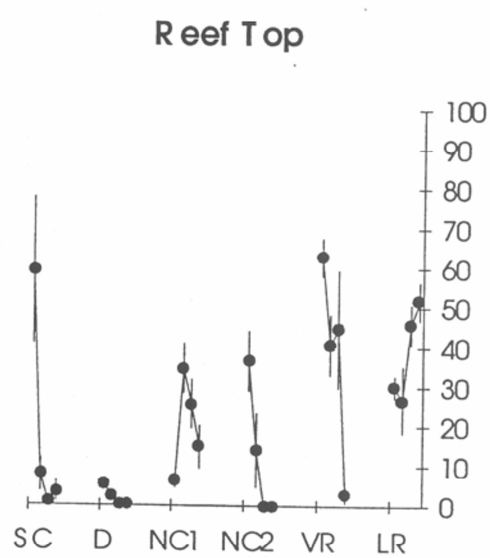


Figure 41: *Total percent cover all corals*

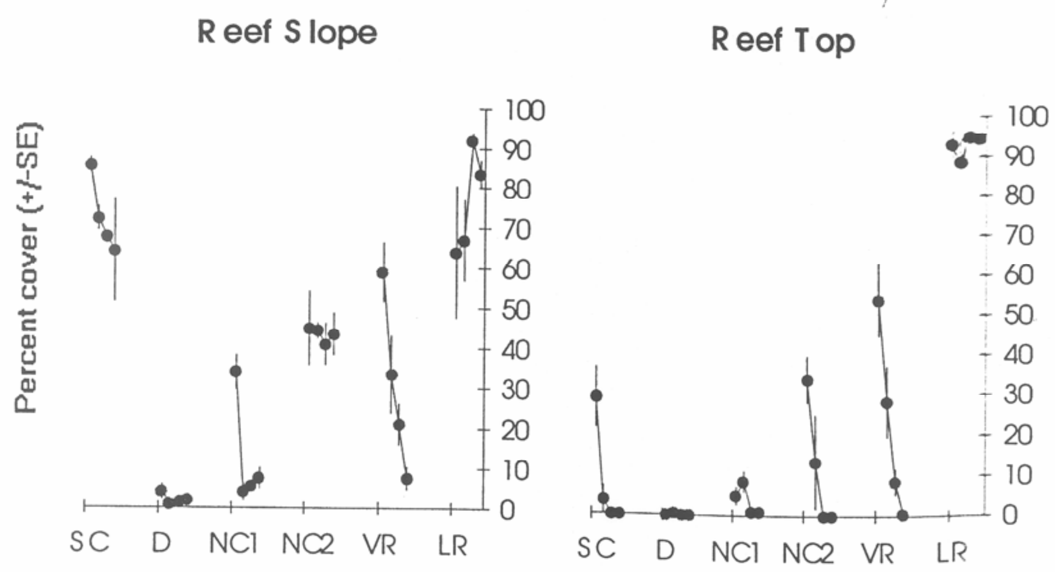
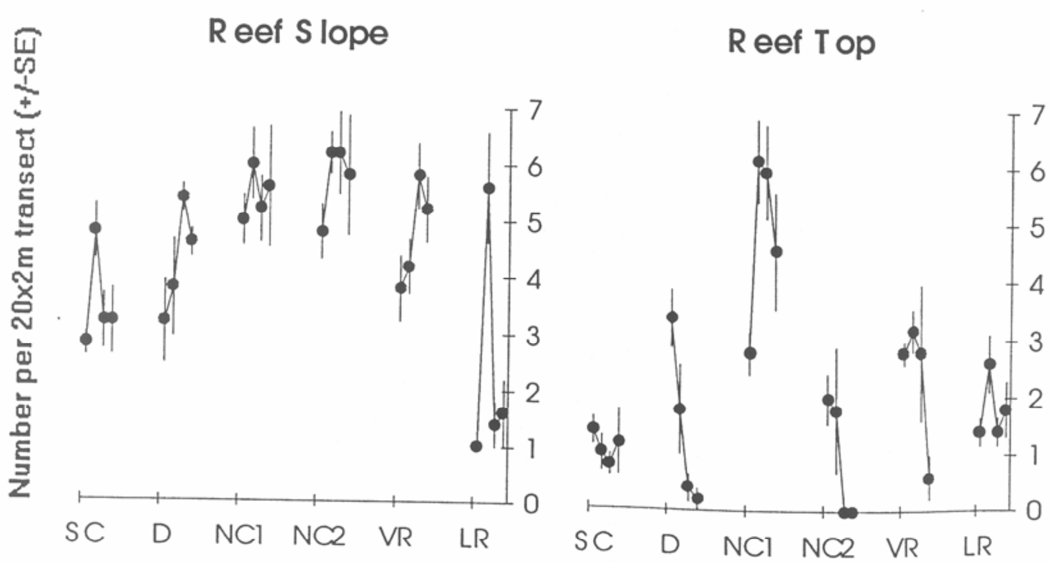


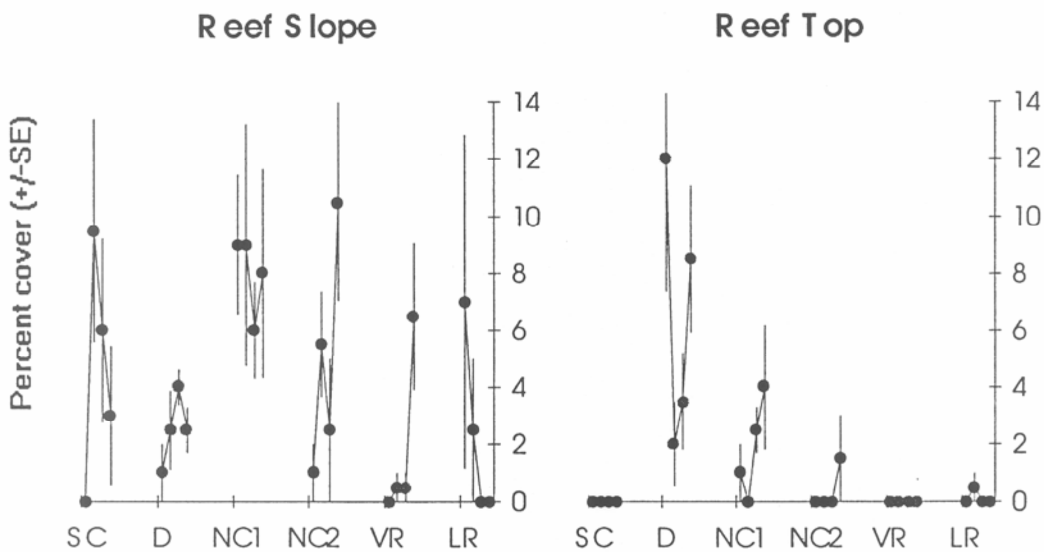
Figure 42: *Diversity of coral types*



Sand

The level of sand deposition was variable among sites and times, and there was no obvious increase associated with dredging (Table 6, Figure 43). The reef top habitat at D underwent a considerable decline between the first two sampling dates, which was substantially reversed after dredging began. This may have been caused by dredging. There was also an increase in sand cover on the slope of Vaiaku Reef, which was only observed at one of the four controls.

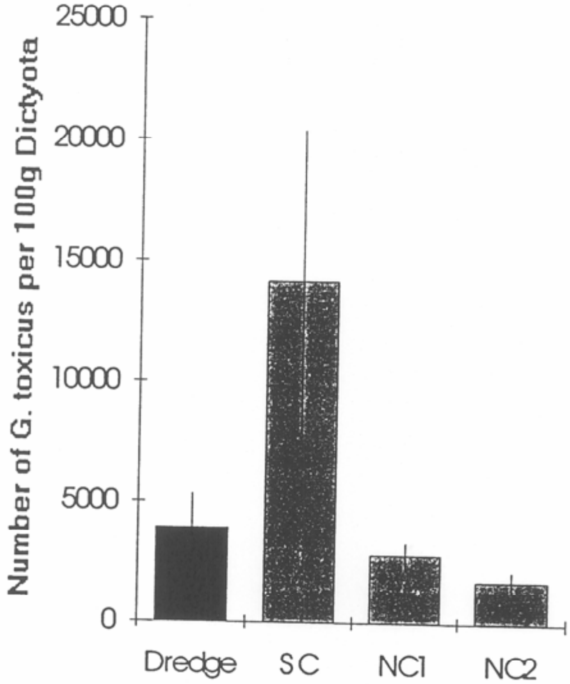
Figure 43: *Percent sand*



Ciguatera

Dredging did not appear to have resulted in elevated levels of the ciguatera-causing microalga, *Gambierdiscus toxicus at D* relative to controls. The abundance of *G. toxicus* at D during Trip 3 was within the range found at SC, NC1 and NC2 (Figure 44). The highest densities of these dinoflagellates was actually recorded from SC with 14,000 cells per 100g of host algae. Densities found at D were under 4,000 cells per 100g host.

Figure 44: Abundance of ciguatera-causing *Gambierdiscus toxicus*



2.4 Discussion

Major spatial patterns in the data (differences among sites, and between dredge impact and control sites) were apparent prior to the initiation of the dredging programme. Dredge sites were generally characterised by lower densities and cover of some corals compared with controls, higher algal cover, higher densities of holothurians, higher densities of fish associated with algal or bare substrata, and lower densities of fish associated with live coral. Pre-existing differences between dredge and controls sites were detected in approximately one third of comparisons made, and in many cases the magnitude of the difference was 2-3 fold.

Two explanations of these pre-existing patterns are possible. Firstly, the benthic and fish communities may reflect historic human impacts in the region where dredging was to occur. High algal cover / low coral cover is generally associated with heavily impacted coral reefs and this situation can persist long after impacting processes have ceased (e.g. Hughes, 1993). Changes to the fish community are generally associated with such changes to the structure of the benthic habitat (Sano, *et al.*, 1984). The alternative explanation is that the differing community structure near the dredge site may reflect a natural gradient toward more sheltered conditions at this site. We favour the former explanation, as the degraded sites more closely correspond to historic coastal developments than the gradient in exposure. The two explanations are, however, not mutually exclusive.

Some impacts of the pilot dredging project were detected by the end of the "During" surveys. These effects included both greater increases at impact sites relative to controls and greater decreases at impact sites than were recorded at controls. However, impacts were detected in only 22% of 164 comparisons and were generally much smaller in magnitude than the pre-existing differences between dredge impact and control sites. The species that tended to increase in relation to dredging were those that were already in greater abundance at the dredge site relative to controls (eg. algae such as *Dictyota*, holothurians, and fish associated with algae or bare substrata such as the wrasse *Halichoeres margaritaceous*). Those that decreased included corals that were already lower in abundance (eg. staghorn *Acropora*) and fish associated with live coral (eg. *Chaetodon trifasciatus*). That is, dredging appeared to be reinforcing the differences that already existed between the dredge and control locations. The effects were typical of those associated with sand dredging, which appears to contribute to a shift from coral-dominated to algal-dominated habitat.

Deterioration of coral reefs resulting from increased sedimentation onto corals and turbidity of the water above them has been reported from all major coral reef areas of the world (Stafford Smith & Ormond, 1992). The mechanisms of damage to corals themselves are through both direct and indirect effects. Sediments overlying tissues may cause smothering (Rogers 1983) or precipitate bacterial infections (Hodgson, 1990) or may interrupt energy budgets by directly restricting feeding activities of coral polyps and/or causing them to spend time and energy on rejection of the sediments (Dallmeyer *et al.*, 1982). Turbid waters over corals and overlying sediments may also interrupt light absorption by symbiotic zooxanthellae whose primary production forms an important part of coral nutrition. Suspended sediments in turbid waters may cause abrasion to delicate coral tissues (Loya, 1976; Rogers, 1983) and layers of sediment