The Effects of Increased Sedimentation on the Recruitment and Population Dynamics of Juvenile Corals at Cape Tribulation, North Queensland

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EXECUTIVE SUMMARY

When an unsealed road was pushed through coastal rainforest in the Cape Tribulation region in late 1984, there were fears that increased run-off from the road might damage the inshore fringing reefs in the region, which was within the Great Barrier Reef Marine Park. A large multidisciplinary research project was established by GBRMPA to examine the effects of the road. This study forms a part of that larger project.

The aims of this study were to investigate the effects of increased sedimentation on the early life history stages of the corals, i.e. coral recruitment onto settlement plates and the recruitment and mortality of small corals. The region was divided into three zones which were predicted to be affected by the construction of the road to varying degrees. Two reefs were studied in each of the three zones, and the coral population parameters were compared among the zones.

At some sites, density of coral spat on settlement plates during the summer period was the highest ever reported in any study of coral recruitment. Very few corals recruited during winter. There was a tendency for more spat settlement on plates in the central and northern zones, compared with the southern zone. There was also a tendency for a corresponding higher rate of mortality of spat on the plates towards the north. Qualitatively different spat settlement patterns (at family level) were observed at different reefs which suggests that there is not a single larval pool available at all the study reefs. The recruitment study indicated that the availability of coral larvae did not correlate with the predicted pattern of increased sedimentation in the region of the new road.

Juvenile corals (i.e. 1cm to 20cm diameter) recruited at similar rates on natural substrata at all reefs. Migration of colonies and fragments of colonies contributed more to successful recruitment than larval settlement, especially for the dominant genera (*Acropora* and *Montipora*). In general, there was no difference in mortality rates of juveniles among any of the study reefs except for one reef in the southern zone which was most affected by a cyclone in early 1986. Again, these patterns did not correlate with the predicted increased sediment from road run-off.

In general, recruitment of coral larvae is limited by the availability of hard substrata for settlement. At Cape Tribulation, the low larval recruitment apparently reflects inadequate substrata and recruitment of coral fragments is a significant factor in the determination of coral community structure under these circumstances.

The hydrodynamics of the region, the heterogeneous nature of reef types, and variation in the degree of exposure mean that there is large local variation in the effects of physical and oceanographic parameters such as waves, currents, eddies etc. The Cape Tribulation reefs have grown throughout their history in an environment of heavy terrigenous influx. (Johnson and Carter 1987). It is unclear to what extent present influx is affecting the reefs as compared with resuspension of muddy bottom sediment.

Two physical events, a cyclone and a coral bleaching episode in successive years, had a significant impact on the coral community during the study period. Any deleterious effects attributable to the road could not be detected, firstly, because of the effects of the two major physical events during the period, and secondly, because the study lacked an effective 'before road' control. Caution should also be exercised in the interpretation of the results of the study because of its relatively short term nature.

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INTRODUCTION

The fringing reefs along the coastline to the north and south of Cape Tribulation are the most extensive on the east Australian coast (Craik and Dutton 1987). A checklist of scleractinian corals on the reefs includes 141 species belonging to 50 genera, including three species not recorded elsewhere on the Great Barrier Reef (Veron 1987).

The reefs consist of a primarily dead erosional reef flat with macroalgae on the outer edges, and a living coral zone from 1.4m depth to a maximum of about 8m depth (Ayling and Ayling 1985; Johnson and Carter 1987; Craik and Dutton 1987). The living coral zone is a veneer over a porous unconsolidated base composed mostly of rubble and is due to cyclonic activities (Hoyal 1986) coupled with a paucity of cementing organisms. Ayling and Ayling (1985) noted two types of reef slope morphology, one shallow (2 to 3m) and the other deeper (5 to 8m), with the latter type generally being more extensive and wider than the first.

The region is famous for the proximity of dense tropical rainforest to the foreshore, and the forest contains many small creeks that empty into the coastal waters. The region typically has high rainfall (average annual rainfall at Cape Tribulation is 3750mm (Bureau of Meteorology 1971)). The prevailing winds are from the north-east during the wet season and from the south-east during the winter trade wind season when long periods of rough conditions occur along the coast. In addition, the region is prone to periodic cyclonic conditions (Ayling and Ayling 1986), and several small cyclones affected the area during the study period.

The combination of coastal streams and weather conditions results in generally turbid conditions along this part of the coastline. The effect of turbidity in reducing light levels may limit coral growth below the depths at which it has been observed in this area. Most turbidity results from the resuspension of fine mud and silt, and corals that survive on these reefs must generally be adapted to low light levels and high sediment fall-out (Johnson and Carter 1987; Cortes and Risk 1985).

In late 1984, amid protests from conservationists, a controversial decision was made to construct an unsealed road through the coastal area north from Cape Tribulation to the Bloomfield River (figure 1). One of the environmental concerns expressed about the road and its manner of construction was that any increased sediment run-off might damage the fringing reefs (Bonham 1985; Veron 1987; Hoyal 1986). Of particular concern was the effect that increased sedimentation might have on scleractinian corals some of which are known to be affected by sedimentation rates above ambient levels (Bak 1978; Lasker 1980; Cortes and Risk 1985).

The environmental study programme designed to monitor the effects of the road on the fringing reefs at Cape Tribulation was initiated in 1985, and is described in Craik and Dutton (1987). The section of the study described here was intended to supplement the large scale biological monitoring of the reef communities by A.M. and A.L. Ayling. The purpose of the study was to examine the recruitment patterns of coral spat, and the early stages of the life history of the corals; and to determine if increased sedimentation had adverse effects on these small corals, even if other monitoring programs could not detect changes in the established and larger corals.

STUDY DESIGN

The study design was similar to that of other studies run concurrently i.e. a comparison between reefs in 3 pre-defined zones, the first (south zone) adjacent to an older and presumably stable road in the south of the region; the second (central zone) adjacent to the recently-constructed road; the third (north zone) to the south of the Bloomfield River where no rivers emptied onto the coastline so that the reefs should be unaffected by increased sediment and should act as a 'control' site.

In the absence of prior information on hydrodynamic conditions (a study was carried out concurrently by Hoyal) it was assumed that reefs would be most affected adjacent to the areas of sediment input from coastal rivers. The objectives of the study were:

1. to compare spat recruitment onto artificial substrata in the three experimental zones in both summer and winter periods;

2. to compare the population dynamics (recruitment, mortality and growth) of juvenile corals in the three zones on an annual basis;

3. to assess the contribution of coral recruitment as a determinant of reef community structure;

4. to correlate differences in coral population characteristics among the three zones with environmental conditions at the sites and the extent to which they had been altered from ambient levels.

Very little information has previously been published on the population dynamics of corals on fringing reefs. Bull (1982), Morrissey (1980) and Heyward and Collins (1985), have reported on coral distribution and reproduction at Magnetic Island, near Townsville, while Harriott (1983, 1985) studied reproduction and recruitment of corals on the fringing reefs surrounding Lizard Island. Much recently available information on Australian fringing reefs is included in Baldwin (1987).

METHODS

Reefs selected for the study were a subset of those studied by Ayling and Ayling (1985), and are shown in figure 1. Their nomenclature was adopted for ease of comparison. In October 1986, the study site at reef No. 3/10 could not be relocated, and a seventh reef (No. 3/9) was included in the study from that time on. The timetable for study periods and natural events during the study is given in table 1. The study had two parts: the first to determine recruitment of coral spat onto artifical settlement plates at each site, and the second an analysis of small corals mapped in $1m^2$ quadrats.

Coral spat recruitment

For the study of coral spat recruitment, two settlement racks were deployed approximately 3m to 5m apart at each of the six reefs. All racks were in water depth of 2 to 3m. Plates were collected and replaced twice yearly, after summer (April/May) and after winter (October/November).

During the first two six-month periods (summer 85/86 and winter 86), the type of settlement plates used was two pairs of coral blocks cut from colonies of massive *Platygyra* sp., and a piece of *Acropora palifera* (Fisk and Harriott 1987). Following a separate study comparing the effectiveness and efficiency of different types of settlement plates (Harriott and Fisk 1987), the remaining spat results were collected using ceramic tiles.

Four pairs of tiles were attached to each rack, with two pairs of horizontal and two pairs of vertical plates. Plates were attached to the rack by a bolt placed through a hole drilled in the centre of the tile. Because of the shallow depth of the settlement racks and rough weather conditions during some periods of the study, entire racks were occasionally lost from the reefs. This is discussed further in the results section. In many cases, some tiles or tile pairs were lost from racks. Generally, at least two of the four pairs of tiles remained, so one vertical and one horizontal pair of tiles were usually taken as the standard sample unit and were analysed. In 1987/88, more tiles were lost from some racks, so one pair of vertical tiles from each rack were used for some comparisons. As large numbers of spat settled on all surfaces, the reduction in the number of tiles to be analysed was not expected to decrease the sensitivity of the data set.

The upper surfaces of the horizontally oriented plates were frequently coated with a layer of fine silt up to 5mm thick. Once collected, tiles were labelled, cleaned and bleached in a solution of chlorine. Coral spat were identified to family level where possible. A record was kept of whether each coral spat was apparently alive or dead at the time of collection. This was determined by the degree of erosion and discolouration of the skeleton.

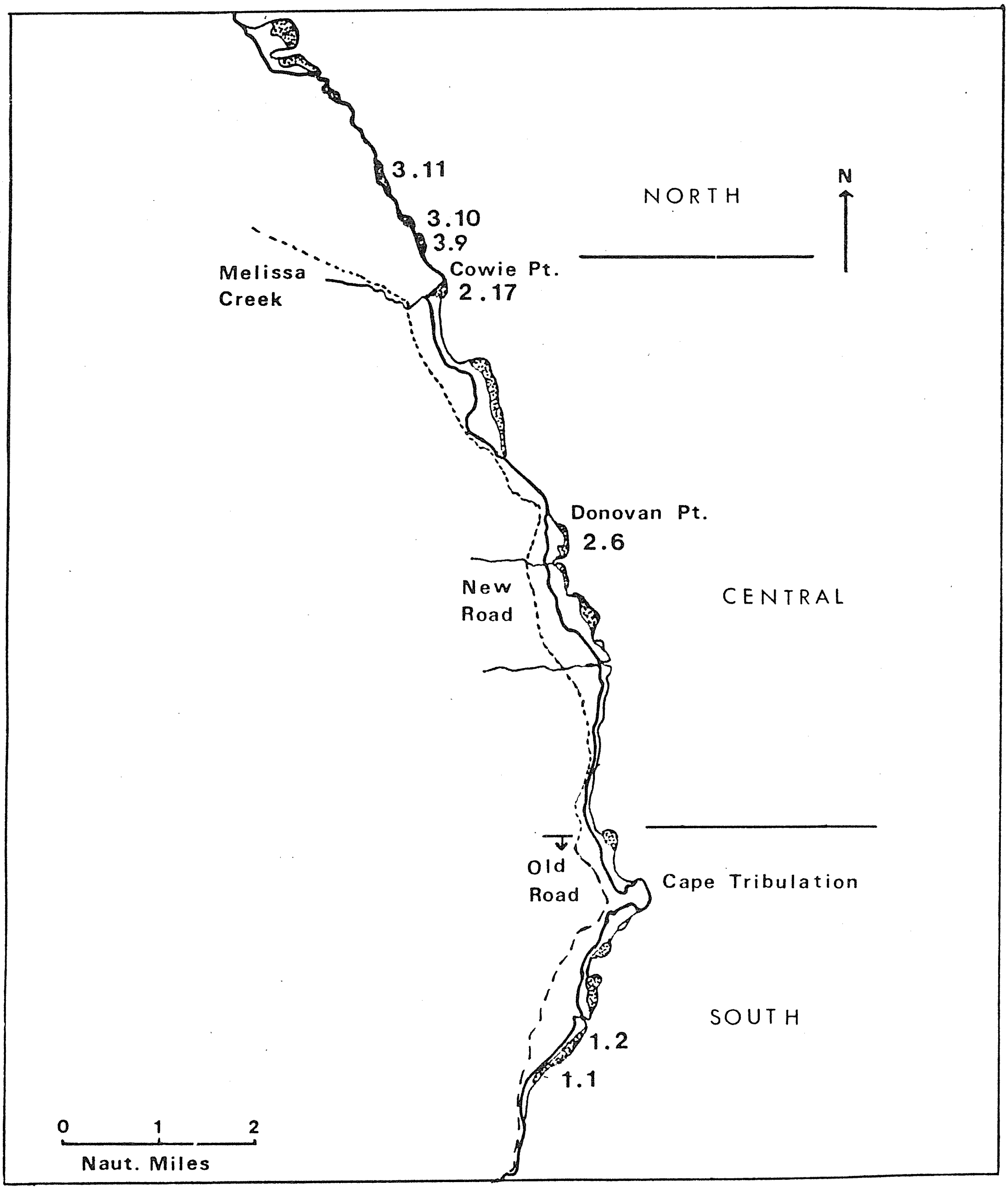

Figure 1. Location of reefs in study area. Zones referred to in the text are shown along with the individual reef numbers. The location of the old and new portions of the road are marked.

Table 1. Timetable for the field project

Time	Event
Late 1984	Road construction
Late 1985	Multidisciplinary study designed and initiated
October 1985	Settlement plates installed. (coral surfaces)
November 1985	Initial juvenile maps
Jan-April 1986	Cyclones Winifred and Namu and rain depression Vernon
April 1986 and June 1986	Settlement plates (coral surfaces) collected and replaced with tiles (on two separate trips due to bad weather)
October 1986	Settlement plates collected and replaced. Additional juvenile quadrats mapped. Reef 3/10 replaced by reef 3/9
Jan-Feb 1987	Coral bleaching
May 1987	Settlement plates collected and replaced
October 1987	Settlement plates collected and replaced Juvenile quadrats mapped
April 1988	Settlement plates collected

Positive identification of coral spat even to family was difficult, partly because many of the types of spat encountered differed from those that the authors had most frequently recorded in previous studies of mid-shelf reefs. In Fisk and Harriott (1987), the second most abundant category of spat at Cape Tribulation was identified as belonging to the family Faviidae. Subsequently, with study of increased numbers of spat, and with access to the coral spat raised from known parents by Dr Russell Babcock (James Cook University), this spat type has been re-assigned to the family Acroporidae, probably the very small juvenile of the abundant plate Montipora species. These species are not abundant on the mid-shelf reefs studied previously, and in its early stages the morphology of the spat resembles that of a small faviid, demonstrating some of the pitfalls in spat identification at this early stage in their taxonomy.

Juvenile coral dynamics

Because of constraints on field time caused by bad visibility, weather and logistics, only three of the intended four replicate $1m^2$ quadrats were marked and surveyed at each site in November 1985. Each quadrat was re-mapped in October 1986, when an additional quadrat per site was added. As mentioned previously, navigational difficulties meant that one of the sites (No. 3/10) was not relocated, and four new quadrats were mapped at site No. 3/9. In October 1986, movement of loose substrate as a result of wave action meant that one quadrat at site No. 3/11 could not be found, so two new quadrats were mapped. All quadrats were re-mapped in October 1987. Mapping involved the recording of the presence/absence of colonies using a previous map drawn from a subdivided quadrat frame; set over fixed stakes. Size was also measured using a maximum diameter and a width perpendicular to this diameter (plus height).

Positive identification in situ was possible to genus level and often species level with the exceptions being very small colonies (<2-3cm dia.) and some larger faviid colonies (5-6cm dia.). Juvenile colonies were defined for the purposes of this study as those with a mean diameter (LxB/2) of less than 20cm. Quadrat sites were selected for their relatively high abundance of small colonies and for having mostly hard substrata within the area. These patches of solid substrata were relatively uncommon in the study areas.

RESULTS

Environmental conditions over the study period

Cyclones and rain depressions

In early 1986, two cyclones impinged on the north Queensland coast. Cyclone Winifred, which crossed the coast between Cairns and Townsville on February 1, 1986, was the first severe cyclone in 14 years to have a major impact on the east Australian coast (Crane 1986). Effects along the Cape Tribulation coast were apparently small (40-50 kn winds were recorded at Low Isles). A rain depression Vernon on the 22-23 January 1986 was mentioned in the meteorological logbook at Low Isles. Cyclone Namu formed to the north of Cooktown in late April 1986 but broke up to the south of Cooktown by 27 April. The effect of this small cyclone was quite severe on some of the reefs in the study area (Ayling and Ayling 1987; this study). No cyclones were recorded in 1987.

Bleaching

The summer of 1986/87 was characterised by calm conditions and a late summer wet season which meant low cloud cover over much of the most intense summer period. Extensive bleaching of scleractinian and some alcyonarian corals was reported along Cape Tribulation reefs and was thought to have commenced some time between 15 January 1987 and 26 February 1987 (Ayling and Ayling 1987). Some bleaching down to 5m depth was still evident in May 1987 but was mainly restricted to partial bleaching in some pocilloporids, *Montipora* spp. and some alcyonarians (Fisk 1987).

Sedimentary regime

Bonham (1985) identified three high impact areas due to the new road construction - north of Cape Tribulation, Donovan Point and Cowie Point. Bonham also pointed out that substantial amounts of sediment from the road had reached the marine environment. At low tide this turbid water is carried onto the living coral zone of the reefs and wave action helps deposition there (Bonham 1985). Fresh/brackish water floats from creeks are also transported in longshore currents driven by prevailing winds (Bonham 1985).

There is also extremely high turbidity due to re-suspension of fine bottom sediments which are in situ along the coast. The net northerly flow of water and suspended sediments occurs most of the year from February to October due to moderate south-easterly winds (10-20kn, (Pickard 1983)). Net southerly flow is expected for the other three months of the year when northerly winds are common. Continuous re-suspension of sediments means that fine turf algae will trap large amounts of sediment and this will reduce substrata available for coral settlement.

Belperio (1983) concluded that fine terrigenous silt and mud are contained within the inner shelf waters (0-20m depth) and that there is continuous deposition and re-suspension as they move north. Hoyal (1986) also found an increase in fine sedimentation from the south to the north, though he could not conclude that there was a significant increase in fine sediment in the nearshore environment due to road construction. He did, however, find red coloured sediment in sediment traps which were inshore close to road disturbance areas but was not in traps in any other places. This could be interpreted as indicating that sediment from road activities reached the coral zones adjacent to some road areas.

Coral spat recruitment

Coral spat at Cape Tribulation showed a noticeable preference for exposed (outer and inner) vertical or near vertical surfaces compared to spat on mid-shelf reefs (Harriott and Fisk 1988) for similar depths. We interpret this as a need to maximise light and minimise sedimentation compared to mid-shelf reefs where light is apparently not as critical in the shallow depth range and most spat settle in cryptic positions.

Spat recruitment patterns show a distinctive summer dominance in abundance, with small numbers in winter. Winter 1986 and 1987 results are shown in table 2. The settlement surfaces differed between the two periods. However, the general trend remains, with low numbers of corals, predominantly of the family Pocilloporidae, settling in winter and mostly in the southern reefs.

Table 2. Winter spat results for 1986 and 1987.

Cut Platygyra plates were used in 1986 and ceramic tiles were used in 1987. Reef 3/10 (1986) was replaced by the adjacent reef 3/9 in 1987. - = no data. All spat are Pocilloporidae except those in brackets. The commas separate spat numbers from each rack (2 racks per reef).

	SOUTH		CENTRAL		NORTH	
Reef	1/1	1/2	2/6	2/17	3/10,9	3/11
Year						
1986	2,1	0,2(1)	0,0	-,-	0,0	0,1
1987	25,10	2(1),10	0,0	0,-	0,0	0,(17)

The northern reef 3/11 in 1987 had a relatively large number of unidentified very young spat. These may have been recruits of a mass spawning species that spawned earlier in summer than usual in this period. This was the case for some species at Magnetic Island that year (R. Babcock, pers. comm.).

All further spat results presented here refer to the summer periods of 1985/86, 1986/87, and 1987/88. The number of days the plates were left in the water varied due to deployment and collection date differences, i.e. 148 days, 228 days, 164 days respectively. Total spat numbers are shown in figure 2, and data for each family are given in Appendix 1. Reef 2/17 did not always have all settlement plates intact or both racks present after any summer period, which at least partially accounts for the lower total spat numbers for this reef. The 1985/86 summer totals are from cut Platygyra plates which represented much lower total surface areas per rack than the ceramic tiles used in the following two summers.

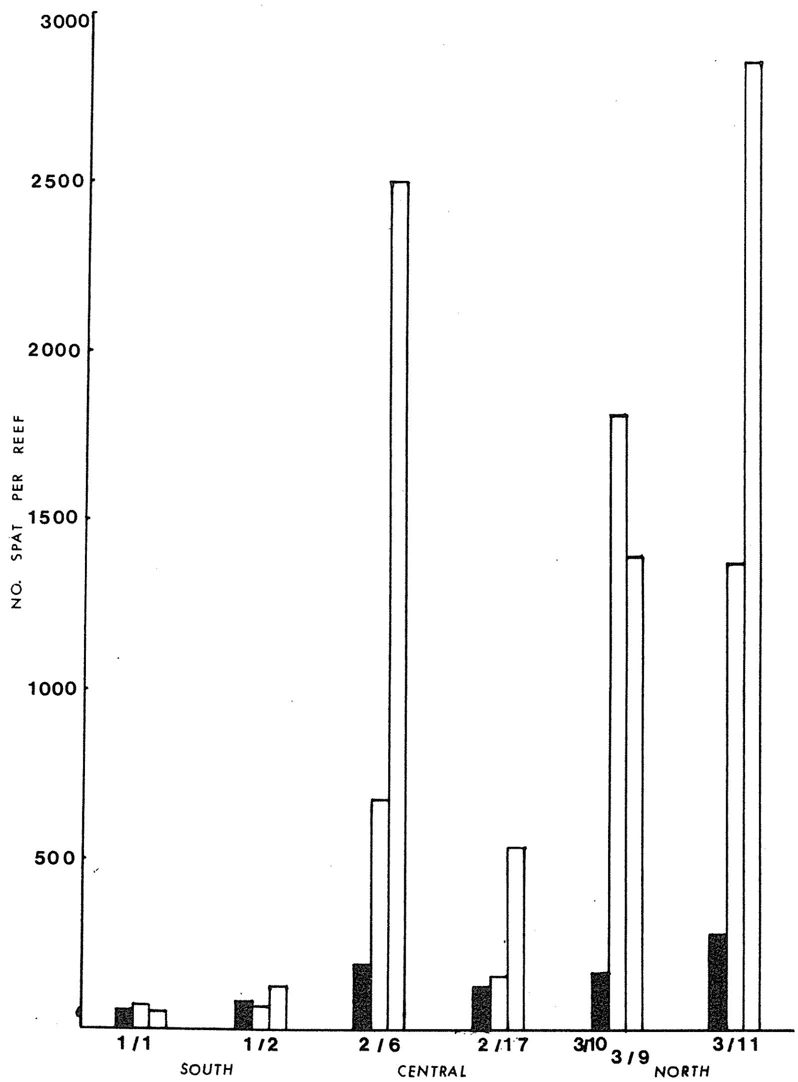

Figure 2. The abundance of spat on settlement plates for the summer periods : 1985/86 (dark, plates of cut Platygyra); 1986/87 (middle plot, plates of ceramic tiles). The number of spat refer to the total number recorded on each reef using a standardised sub-sample of settlement surfaces per rack from 2 racks on each reef. Reef 2/17 usually did not have all tiles remaining on racks in 1986/87 and 1987/88, accounting in part for the lower total abundances at this reef.

Analysis of spat data was approached by treating each summer period separately because the factor years is not an independent variable due to replacement racks being re-deployed in exactly the same position. The data for 1985/86 and 1987/88 were analysed using a 1-way ANOVA block design analysis to test for differences between zones. Because of missing racks, this analysis could not be used on the 1986/87 data. The 1986/87 and 1987/88 data were analysed by reefs using 1-way ANOVA with Tukeys test to distinguish reefs that significantly varied (at 0.05 level) from each other. The relative proportions of each family within a reef set of plates was used to test if coral larvae were from a single well mixed larval patch from which all reefs could receive recruits.

Summer 1985/86

The number of spat per rack ranged from 30 to 450 (mean = 151, SD = 108, no. racks = 12). There was no significant difference in the number of spat per rack between reefs but the number of poritid spat was relatively consistent between the 3 zones (1-way nested ANOVA, F = 2.61, P(f) = 0.13, df = 2,9). The number of poritid spat was relatively consistent between reefs but the number of acroporid spat varied greatly (Appendix 1). However, the proportion of all spat represented by the pocilloporid, acroporid, and poritid families did not vary significantly between zones (1-way nested ANOVA, F = 2.95, P(F) = 0.1; F = 3.07, P(f) = 0.1; F = 4.41, P(F) = 0.06, respectively).

Summer 1986/87

The number of spat per rack (totals from 1 pair each of horizontal and vertical tiles) ranged from 21 - 1111 (mean = 378, SD = 369, no.racks = 11) (Appendix 1). There was a significant difference in the total number of spat per rack between reefs (1-way ANOVA, F = 15.35, P(F) = 0.005; df = 5,5; 1 rack from reef 2/17 lost). Further analyses using Tukeys tests showed that the differences were due to zonal differences. That is reefs 1/1, 1/2 (South zone) had significantly smaller numbers of spat than reefs 3/9 and 3/11 (North zone). Also, reef 3/9 had significantly higher spat numbers than reefs 2/6 and 2/17 (Central zone).

The proportions of some of the major spat families (acroporids and poritids) varied significantly between reefs (P(F) = 0.004,0.0000, respectively) (Appendix 1). Pocilloporids and faviids did not vary significantly (ANOVA, P(F) = 0.06, 0.0773, respectively) but this may be due to relatively low numbers of these 2 families represented on the tiles. The significant difference in the proportion of acroporids was due to the high numbers of acroporid spat on the northern reefs (3/9 and 3/11). The proportion of poritidae differed because of large (1/1) to very large (1/2) relative numbers in the southern zone reefs and a larger proportion on one rack at reef 2/17 (central), compared to lower numbers at reefs 2/6 (central) and 3/9, 3/11 (north).

ANOVA (1-way) of differences in the proportion of live spat on plates at the time of collection revealed a significant difference between reefs ($F = 8.54$, $P(F) = 0.0172$, $df = 5,5$) due to significantly higher numbers of live spat at reef 1/2 compared to reefs 2/6, 3/9, and 3/11. There is a trend towards a higher proportion of live spat in the southern zone compared to the central and northern zones.

Summer 1987/88

The number of spat per rack (using 2 vertical, 2 horizontal pairs) ranged from 21 to 1664 (mean = 622, SD = 602, no.racks = 12; Appendix 1). Because rack number 1 from reef 2/17 had no remaining horizontal plates, spat per reef were compared using one pair of vertical plates per rack.

Results of the nested ANOVA to test for differences between zones showed no differences for total number of spat per zone, as well as for the proportion of faviids, acroporids, poritids, or live spat. The proportion of pocilloporids did differ with the southern zone having the highest relative proportions.

When the reefs within each zone were analysed separately, there was a significant difference in the total number of spat per reef (1-way ANOVA, $F = 12.07$, $P(F) = 0.004$, $df = 5,6$). Tukey's test showed significantly higher numbers on racks at reef 3/11 and 2/6 compared to reefs 1/1, 1/2. Reef 3/11 was also significantly different from 2/17.

The relative proportion of acroporids and pocilloporids differed significantly between reefs ($F = 7.96$, $P(F) = 0.013$; $F = 92.68$, $P(F) = 0.0000$, respect.) with higher proportions of acroporids in central (reef 2/6) and northern reefs (reef 3/11) compared to reef 1/1 (south). Also, there were significantly higher proportions of pocilloporids on the southern reefs (1/1, 1/2) compared to all other reefs. The poritids and faviids did not differ significantly between reefs in their relative proportions ($F = 2.59$, $P(F) = 0.139$; $F = 0.862$, $P(F) = 0.555$, respect.). The actual numbers of each spat family did vary between reefs but not necessarily in the same way as their relative proportions.

There was no significant difference in the proportion of live spat on the plates from any reef (ANOVA, $F = 4.12$, $P(F) = 0.0571$, $df = 5,6$).

Juvenile coral dynamics

In November 1985, 29 genera were recorded from the 36 permanent quadrats and in subsequent years an additional 9 genera were recorded in a total of 42 quadrats (Appendix 2).

Acropora spp. and Montipora spp. dominated all sites (in the no.colonies/quadrat) while most other genera were patchy over the study reefs. Representation of genera within a reef ranged from 21-58% of the total number of genera recorded over all the quadrats. The southern two reefs had 39% of all recorded genera present, while the central and northern zones had 76% and 66%, respectively.

Abundance, recruitment, and survival rates for the major juvenile families were calculated for the two-year period of the study from 1985 to 1987 (table 3). Additional data are given for the most abundant family, Acroporidae (table 4).

Survival rates

There was a significant difference in the survival rates of all corals between reefs over the two-year period (ANOVA, $F = 6.37$, $P(F) = 0.01$, $df = 4,9$). Tukey's tests showed a difference in survival between reef 1/1 and the other 4 reefs (data for reef 3/9 did not span the two-year period and were not included in this analysis).

Recruitment

Recruitment of corals (at visible size) measured here included both migration of colony fragments from outside the quadrats and larval recruitment. Daughter colonies produced through fission of a single large colony also contribute to an increase in the number of colonies but this occurred infrequently and is not included in the recruitment estimates.

Overall, recruitment rates into permanent quadrats were not significantly different between any of the reefs over both year periods (1985-86: $F = 1.92$, $P(F) = 0.192$, $df = 4,9$; 1986-87: $F = 1.61$, $P(F) = 0.21$, $df = 5,18$). However, in 1986-87 the acroporids showed a significant difference in recruitment rates ($F = 3.89$, $P(F) = 0.014$, $df = 5,18$), which was due to a higher recruitment at reef 1/1 (south) compared to reefs 2/6 and 2/17 (central) (Table 4).

Size frequency plots of juveniles (figure 3) show that relatively large numbers of colonies of both Acropora and Montipora, particularly in the size class of 6-10 cm mean diameter, were contributing to the high recruitment rate in the southern zone reefs. The size ranges of recruits suggest that recruitment is mainly via migration of larger colonies into the quadrats, rather than from recruitment of larvae.

Table 3. **Survival and recruitment of juvenile colonies.**

For the two-year period from 1985-87 and grouped into major families and pooled minor families (others). The minor families include representatives from Dendrophylliidae, Oculinidae, Fungiidae, Caryophylliidae, Merulinidae, Pectiniidae, Agariciidae. Only 1 reef in the northern zone was followed for the two years and 2 quadrats in this reef were followed compared to 3 quadrats at all other reefs. Data presented as % survival and (initial no.).

	SOUTH		CENTRAL		NORTH
Reef	1/1	1/2	2/6	2/17	3/11
Survival Rates:					
F.Acroporidae	11%(106)	29%(136)	31%(33)	47%(15)	30%(20)
F.Pocilloporidae	0 (8)	30%(10)	0 (2)	0 (3)	0 (1)
F.Poritidae	0 (0)	33%(9)	30%(23)	50%(2)	27%(11)
F.Faviidae	20%(5)	29%(7)	76%(21)	73%(11)	40%(5)
Others	0 (14)	11%(18)	56%(25)	73%(15)	27%(11)
Pooled	10%(133)	27%(180)	45%(106)	59%(46)	29%(48)
Recruitment:					
1986	29	36	29	6	58
1987	60	48	21	7	41

Table 4. **Abundance, recruitment, and relative survival of Acroporids.**

	SOUTH		CENTRAL		NORTH
Reef	1/1	1/2	2/6	2/17	3/11
Initial Nos. (1985)	106	136	33	15	20
% of all Survivors at each reef	92%	80%	25%	26%	43%
% of all Initial corals	79%	76%	35%	33%	42%
Recruitment					
1986	26	27	16	0	25
1967	52	31	9	1	17

Table 5. Relative contribution of spat settlement and colony migration to the recruitment rates (mean recruits/m^2). Recruitment into permanently marked quadrats for the two-year period 1985-87. Figures refer to the combined totals of each family grouped into zones. Size refers to mean diameter in cm; recruits in the <2.5cm size class are assumed to be from spat settlement, and recruits in the >2.5cm size class are assumed to have resulted from colony migration.

	SOUTH		CENTRAL		NORTH	
	<2.5	>2.5	<2.5	>2.5	<2.5	>2.5
No.Perm.Quads.	14		14		10	
Acroporids	0.77	5.6	0.28	1.0	0.34	4.4
Pocilloporids	0.03	0.43	0.0	0.07	0.07	0.2
Poritids	0.03	0.36	0.15	0.3	0.14	0.1
Faviids	0.0	0.07	0.22	0.21	0.14	0.1
Other	0.16	0.5	0.32	0.64	0.31	1.1
Totals	2.2	6.9	1.36	2.2	2.9	5.9

To gauge the relative contribution of spat settlement and colony migration to the recruitment rates, the size class differences between colonies <2.5cm (assumed spat settlement) and colonies >2.5cm (assumed colony migration) are compared (table 4). In all cases, except for the poritids and faviids in the northern zone reefs, the recruitment by migration was greater than spat recruitment.

Mortality rates

Mortality rates of all corals combined showed no significant difference between individual reefs in the 1985-86 year ($F = 3.04$, $P(F) = 0.077$, $df = 4,9$). There was a significant difference between reefs in the following year period 1986-87 ($F = 3.04$, $P(F) = 0.037$, $df = 5,18$). This difference was due to significantly higher mortality rates at reef 1/1 (south) than at 1/2 (south) and 2/17 (central) (Tukey's Test).

Size class distributions

The size frequency distributions of corals within the 3 zones (combined total from 2 reefs in each zone) and for the 3 census periods between 1985-1987 (inclusive) are given in Appendix 3. Numbers are low for all major families except the acroporids, and the 'other families' group includes diverse genera which were usually abundant in one particular reef but rare or absent on most other reefs.

Kolmogorov-Smirnoff tests were conducted on grouped data using proportions of colonies in size frequency groupings, to test if there were significant differences between reefs and years in the size structure of the juveniles (Appendix 4). There was no significant difference in size frequencies between any of the zones in any year period over the study period (Appendix 5). However, two zones showed significant differences (at the 0.05 level) in size frequency distributions between two consecutive years. That is, the southern zone reefs differed between 1986 and 1987, and the northern zone reefs showed a significant difference between 1985 and 1986. These differences could be reasonably interpreted as the result of cyclones in the 1985-86 period at least.

Relationship between spat and juvenile abundances

Table 5 gives the proportion of each of the major families recorded on settlement plates for the two-year period from October 1985 to October 1987, and a corresponding estimate of the proportion of each family assumed to be the result of spat recruitment (<2.5cm mean dia.) in permanent quadrats over the same time period. For example, the acroporids showed higher relative proportions in the quadrats compared to plates in the southern zone, but lower relative proportions in quadrats compared to plates in the central and northern zones.

Table 6. Proportions of each hard coral family settling on settlement plates compared to the proportion of each family of visible recruits (<2.5cm mean dia., and overall proportion of juveniles) in permanent quadrats. Data is for the two-year period 1985-87 (incl.). N = no. spat or visible recruits. Ppn. = proportion of total in a particular zone.

	SOUTH			CENTRAL			NORTH		
	Plates	Quadrats <2.5	Quadrats Overall	Plates	Quadrats <2.5	Quadrats Overall	Plates	Quadrats <2.5	Quadrats Overall
Acroporidae:									
Ppn	0.54	0.77	0.8	0.72	0.28	0.22	0.68	0.34	0.54
N	254	24	218	1056	6	36	2797	10	121
Pocilloporidae:									
Ppn	0.19	0.03	0.06	0.001	0	0	0.01	0.07	0.03
N	90	1	16	2	0	0	34	2	6
Poritidae:									
Ppn	0.16	0.03	0.05	0.03	0.15	0.12	0.05	0.14	0.07
N	77	1	15	49	3	19	196	4	15
Faviidae:									
Ppn	0.02	0	0.03	0.002	0.22	0.24	0.01	0.14	0.08
N	8	0	9	3	4	39	37	4	19
Others:									
Ppn	0.01	0.16	0.07	0.24	0.32	0.42	0.26	0.31	0.28
N	45	5	18	349	6	67	1066	9	64
Total									
N	474	31	276	1459	19	161	4130	29	225

DISCUSSION

Correlating differences in life history and recruitment characteristics of coral communities on the six fringing reefs with differences in conditions caused by run-off due to road construction has been difficult for a number of reasons:

1. Major natural physical events (cyclones, bleaching) during the study period caused major effects on coral survival. These appeared to be greater than any factor attributable to increased sediment run-off;

2. No pre-road studies were available to give baseline data for the parameters measured in this study;

3. The northern drift of fine sediments reported in a concurrent study (Hoyal 1986) meant that the sites intended as controls probably received the higher levels of fine sediment. If these hydrodynamic data had been available before the project was designed, sites could have been selected to take this factor into account. Further analysis of Hoyal's data is necessary to determine the significance of sedimentation and its effects.

4. All sediments associated with the reef have high terrigenous contents (>50%), indicating the reefs have always grown under heavy terrigenous influx. (Johnson and Carter 1987) Sedimentological studies (Hoyal 1986; Johnson and Carter 1987) could not distinguish between new sediment from the road, sediment deposited at the reef and suspended sediments. No quantification of increase in sediment levels above ambient was available to correlate with the biological results.

Nevertheless, the study has produced some interesting biological results in one of the few studies of its kind on fringing reefs, and the results point out some major considerations for the design of similar studies in the future.

Coral spat recruitment

Cape Tribulation reefs are in general self-contained within the coastal environment, i.e. they are separate from reefs elsewhere due to coastal dynamics and are unlikely to receive coral recruits from the mid-shelf reefs (Belperio 1983; I.Dight, pers.comm.; D.Hopley, pers.comm.). A good example is the presence of three coral species of these reefs which have not been recorded from elsewhere on the Great Barrier Reef (Veron 1987).

The highest spat densities from any coral reef studied to date were recorded in this study (up to 1098 spat/225cm^2). In comparison, Harriott and Fisk (1988) recorded up to 169 spat/225cm^2 at Green Island Reef and Sammarco and Andrews (1988) reported up to 108 spat/225cm^2 (converted from 600cm^2 settlement area) at Helix Reef.

The increase in spat settlement densities from the southern zone to the central-northern zones parallels the general south to north increase in fine sedimentation rates (Hoyal 1986). This indicates that there was a general northerly longshore drift of both sediment and coral larvae during the study period. Since water dynamics control coral larvae dynamics (Oliver and Willis 1986), and wind speed and direction determine the longshore drift in this area (Pickard 1983), the abundance of larvae along the coast for any given spawning season should be controlled by wind behaviour during the critical 5-7 days of obligate planktonic life of a coral larvae (Babcock 1984). Eddies have also been observed behind headlands (Van Woesik, pers.comm.) which may act as short term larval retention sites and aid in increased coral settlement. This feature could explain how specific reefs recorded consistently high coral settlement rates, e.g. reefs 2/6, 3/9, 3/10.

The differences in the relative abundances of spat families and total spat numbers between reefs and sometimes between zones suggests that there is not a single pool of larvae available to all reefs along this coastline. The relative abundances of some brooding species, e.g. the pocilloporids, affects local spat composition.

The fact that the area of apparently highest fine sediments also had highest coral recruitment indicates that larval availability is not affected by the fine sediment. However it is possible that availability of suitable settlement sites or early survival might have been affected.

In 1986/87, there was higher spat mortality in the more northern sites, which correlates with the higher fine sedimentation rates towards the north. In contrast, in 1987/88, there was no increase in mortality in the more northern sites. In that year, observed sediment deposition on the settlement plates in the northern sites was less than in the previous year. These differences in mortality may have been the result of 62 extra days immersion 86/87 compared to the 87/88 period, or may have been because of higher turbulence over the 1986/87 period.

Juvenile coral dynamics

Twenty-nine of the 50 genera recorded at Cape Tribulation were included in the study of juvenile coral dynamics. Acropora and Montipora corals dominated most quadrats, and species from these genera recruited commonly by fragmentation. The importance of fragmentation on these reefs is reflected in the high mobility of the substrate during the study period. Reef 1/1 in the southern zone was composed almost entirely of these two genera and had low survival rates and higher recruitment from fragments than the other reefs studied.

Apart from high recruitment of acroporids to reef 1/1, there was no significant difference in recruitment rates between reefs during the study period. Poritids and faviids appear to be more dependent on recruitment of larvae than acroporids.

Mortality rates of the juvenile corals did not differ significantly between reefs in either of the one-year periods. (41% to 90% over two years) could not be attributed to increased sediment fall-out from the road construction. Because of the natural episodic events during the study period, increased sediment fall-out from road construction could not be detected.

The difference in size class structure between 1986 and 1987 for the southern zone appears to be due to two factors: an increase in abundance of the 11-20cm mean diameter sizes in 1987 which was probably due to growth, and a corresponding decrease in numbers of colonies in the 0-2.5cm mean diameter sizes, indicating differential mortality leading to lower successful spat recruitment compared to previous years. The northern zone reefs differed in size structure between 1985 and 1986 because of higher numbers of colonies in the 11-15cm mean diameter size class in 1986 compared to 1985. This was probably due to the change in study reefs rather than growth of smaller colonies from the previous year.

The difference between sites in the taxonomic composition of recruits on settlement plates and in quadrats may be attributed to inter-annual variations (spatial and temporal) in recruitment patterns, habitat selection by spat such that the recruitment patterns of juveniles differs from the patterns found on the settlement plates, or differential mortality between recruitment and appearance as a visible colony.

During the study period, recruitment patterns of spat did not differ significantly from year to year. Habitat selection by spat could be expected to be similar from reef to reef. Therefore, differential mortality may be a significant determinant of variation in taxa between spat and juveniles.

For the acroporids, conditions may be more favourable for early survival in the southern zone than in the central and northern zone since they are proportionally better represented amongst the juveniles than in the spat in the south though these data are not sufficiently long term for definite conclusions. The trend is the reverse for the pocilloporids, poritids, and faviids, with juveniles recruiting in greater proportions than spat in the central and northern zones compared to the southern zone reefs (pocilloporids are rare in the central zone). Fragmentation may be contributing greatly to the currently high juvenile acroporid abundances on the northerly reefs.

The fact that size frequency distributions of the coral colonies were similar in the three zones for each of the three periods, implies that there has been no clear impact of increased run-off on the size structure of corals in the impact zone.

IMPLICATIONS FOR MANAGEMENT

The Cape Tribulation reefs are characterised by high natural sedimentation and turbidity and this results in low larval recruitment rates to visible size (despite abundant larval availability), and low light levels, respectively. The dominance of maximum light collection growth forms such as foliose colonies means that sedimentation rates in shallow water are not sufficient to exclude this type of growth. Anthropogenic sediment input must increase the total amount of sediment, but there appears to be no measurable impact of this input to date. Additional input above the normal background levels will continue as long as the road remains unsealed and is routinely graded. This may represent an accumulating chronic long term problem as the reef system is essentially oceanographically self-contained with most processes and their effects remaining within this area.

- It is possible that sediment could accumulate gradually through chronic run-off during wet seasons so that lethal effects can be detected only over a relatively long time. This sediment may also be resuspended during periods of rough weather increasing the problems.

- As data from the sedimentation studies is still being analysed, it is not possible to relate coral larval recruitment and settlement to sedimentation rates at this time.

- Pre-road data is hence imperative for proper assessment of the impact, and it is important that hydrodynamic data be collected early in the project to aid the design of an appropriate study. Correlations of diminishing effects of an impact over distance were hard to determine due to the heterogeneous shape of the coastline (causing eddy effects and variable exposure to water motion), and due to the natural variability in the coral communities.

- To help mobilise a quick response to cases such as this, a readily available source of funds should be kept so that pre-impact data can be collected at short notice.

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APPENDICES

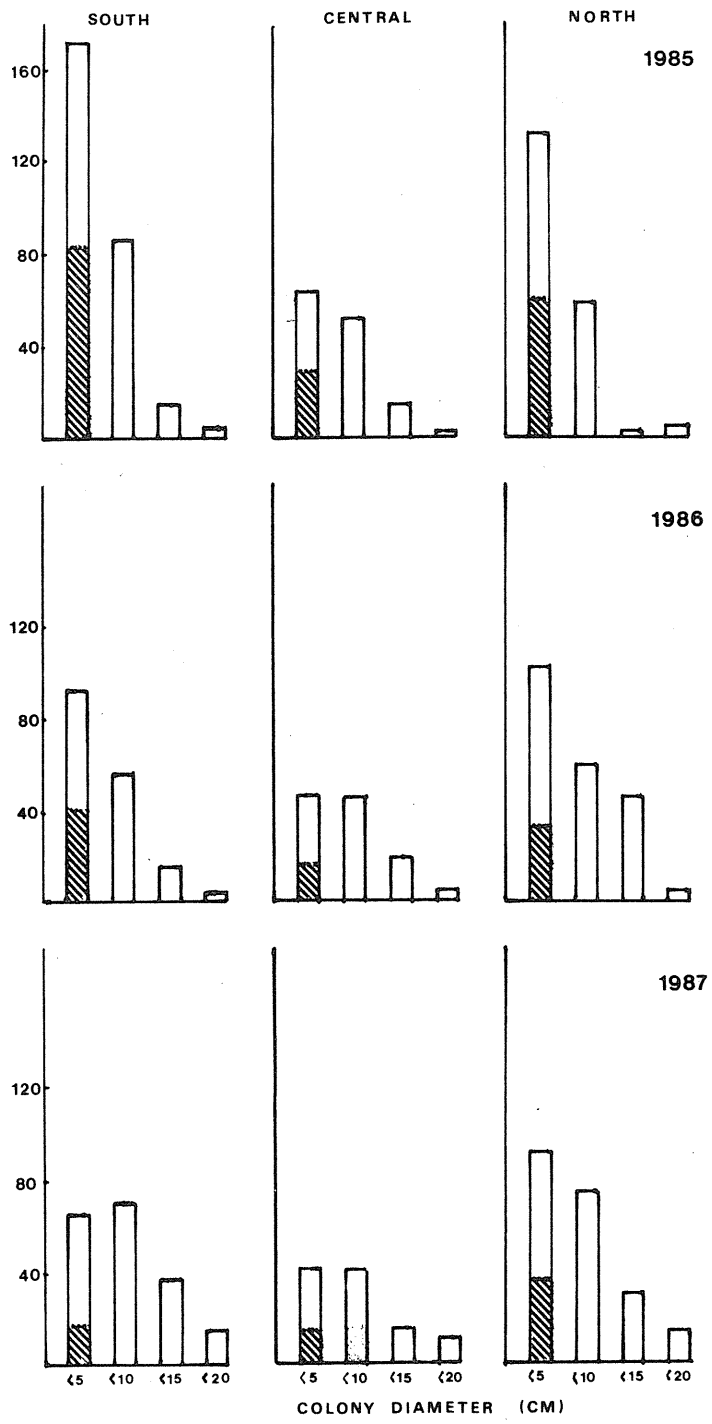
Appendix 1. Summary of spat data for the 3 summer periods of the study.
-= no data. Fav.=Faviidae; Poc.=Pocilloporidae; Acr.=Acroporidae;
Por.=Poritidae; Gal.=Galaxiidae; Oth.=Other.
==not used as a category; in 1985, the faviid individuals would have been included with the 'others' category.
Numbers of spat separated by a comma are the numbers from each rack.

Reef Year	Total per rack	Spat Families Fav.	Poc.	Acr.	Por.	Gal.	Oth.	% Live
1/1								
1985	30, 90	0, 0	5, 3	13, 76	8, 4	=, =	4, 7	=, =
1986	49, 23	4, 2	16, 4	17, 10	7, 4	1, 0	4, 3	78,78
1987	21, 34	0, 0	7, 12	13, 21	1, 1	0, 0	0, 0	62,85
1/2								
1985	41, 123	0, 0	0, 5	31, 86	5, 20	=, =	5, 12	=, =
1986	44, 21	0, 2	6, 0	12, 7	19, 10	0, 0	7, 2	74,81
1987	33, 91	0, 1	6, 15	24, 53	2, 10	0, 2	0, 10	38,47
2/6								
1985	206, 175	0, 0	1, 0	171, 147	5, 9	=, =	29, 19	=, =
1986	345, 329	0, 3	0, 1	236, 203	1, 3	0, 2	108,117	8,16
1987	1219,1275	5, 8	4, 1	1122,1224	33, 15	10,11	45, 16	21, 8
2/17								
1985	129, 120	0, 0	1, 0	115, 103	4, 3	=, =	9, 14	=, =
1986	156, -	0, -	0, -	81, -	24, -	0, -	51, -	35, -
1987	306, 234	7, 0	6, 0	193, 201	68, 9	11, 3	21, 21	65,62
3/9 (3/10 in 1985)								
1985	185, 153	0, 0	8, 1	84, 108	74,24	=, =	19, 20	=, =
1986	1112, 715	8, 11	9, 6	687, 435	20, 31	2, 4	386,228	16,15
1987	382,1013	0, 6	7, 29	337, 808	32,151	0, 4	6, 15	59,61
3/11								
1985	451, 109	0, 0	5, 1	392, 74	22, 10	=, =	32, 24	=, =
1986	710, 677	7, 11	3, 0	554, 462	3, 12	2, 4	141,188	12, 9
1987	1664,1193	1, 2	4, 1	1585,1091	25, 51	3, 3	42, 44	33,30

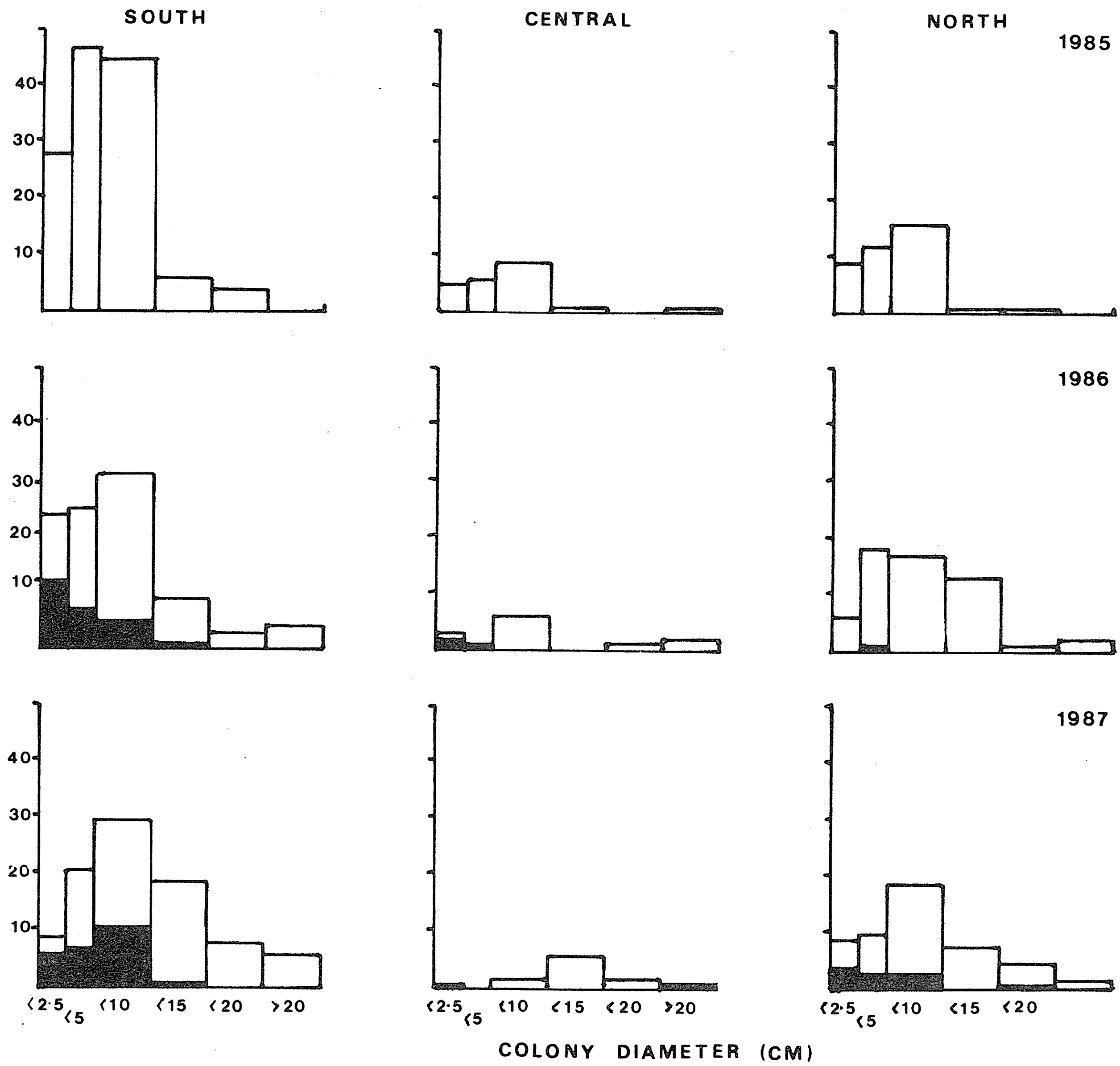
TOTALS	
1985	1812
1986	3194
1987	4252

Appendix 2. Generic composition of juvenile coral community in permanently marked quadrats for the period 1985-87 (inclusive). Date for 1985 census from 3 quadrats; data for 3/11 from 2 quadrats; otherwise, 1986 and 1987 data from 4 quadrats. In 1985, data for northern reef 3/9 is replaced with data from reef 3/10.

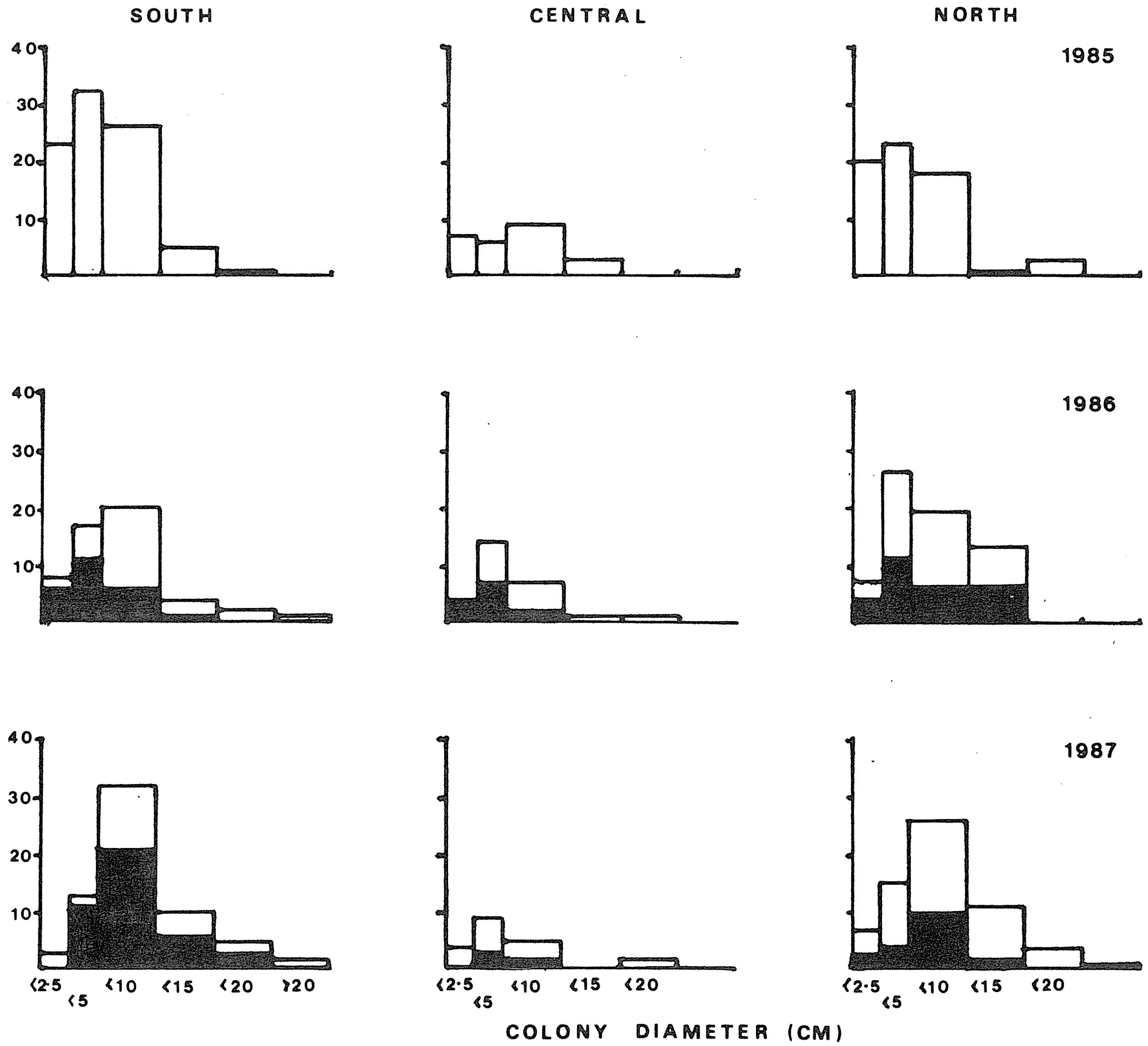
		SOUTH		CENTRAL		NORTH	
	Yr.	1/1	1/2	2/6	2/17	3/9	3/11
Acropora	85	24	98	13	7	37	13
	86	20	78	5	4	35	8
	87	15	80	9	4	35	10
Montipora	85	78	21	15	5	53	9
	86	27	14	20	5	37	25
	87	47	26	18	5	34	23
Fungia	85	7	7	3	0	17	0
	86	3	5	2	0	0	4
	87	1	5	2	0	1	5
Porites	85	0	7	13	0	5	5
	86	0	7	13	1	6	2
	87	0	8	12	1	7	2
Hydnophora	85	6	1	0	2	16	0
	86	0	1	0	2	1	0
	87	0	1	1	0	2	0
Galaxea	85	0	4	7	5	5	4
	86	0	3	9	7	16	1
	87	0	4	13	6	11	3
Pocillopora	85	7	9	1	0	0	0
	86	1	5	0	0	1	0
	87	1	7	0	0	2	0
Favia	85	0	2	8	4	0	2
	86	0	3	11	3	4	0
	87	0	2	10	3	4	0
Favites	85	0	0	6	0	2	3
	86	0	0	3	3	2	2
	87	0	0	5	3	2	0
Turbinaria	85	0	0	0	5	0	3
	86	0	0	0	6	3	1
	87	0	0	0	5	3	1
Goniopora	85	0	0	3	1	0	7
	86	0	0	1	0	0	2
	87	0	0	0	0	0	0
Stylophora	85	1	1	1	3	0	1
	86	2	2	2	3	8	0
	87	1	1	0	0	4	2
Cyphastrea	85	0	0	2	0	1	3
	86	0	0	0	0	1	0
	87	0	0	0	0	0	1



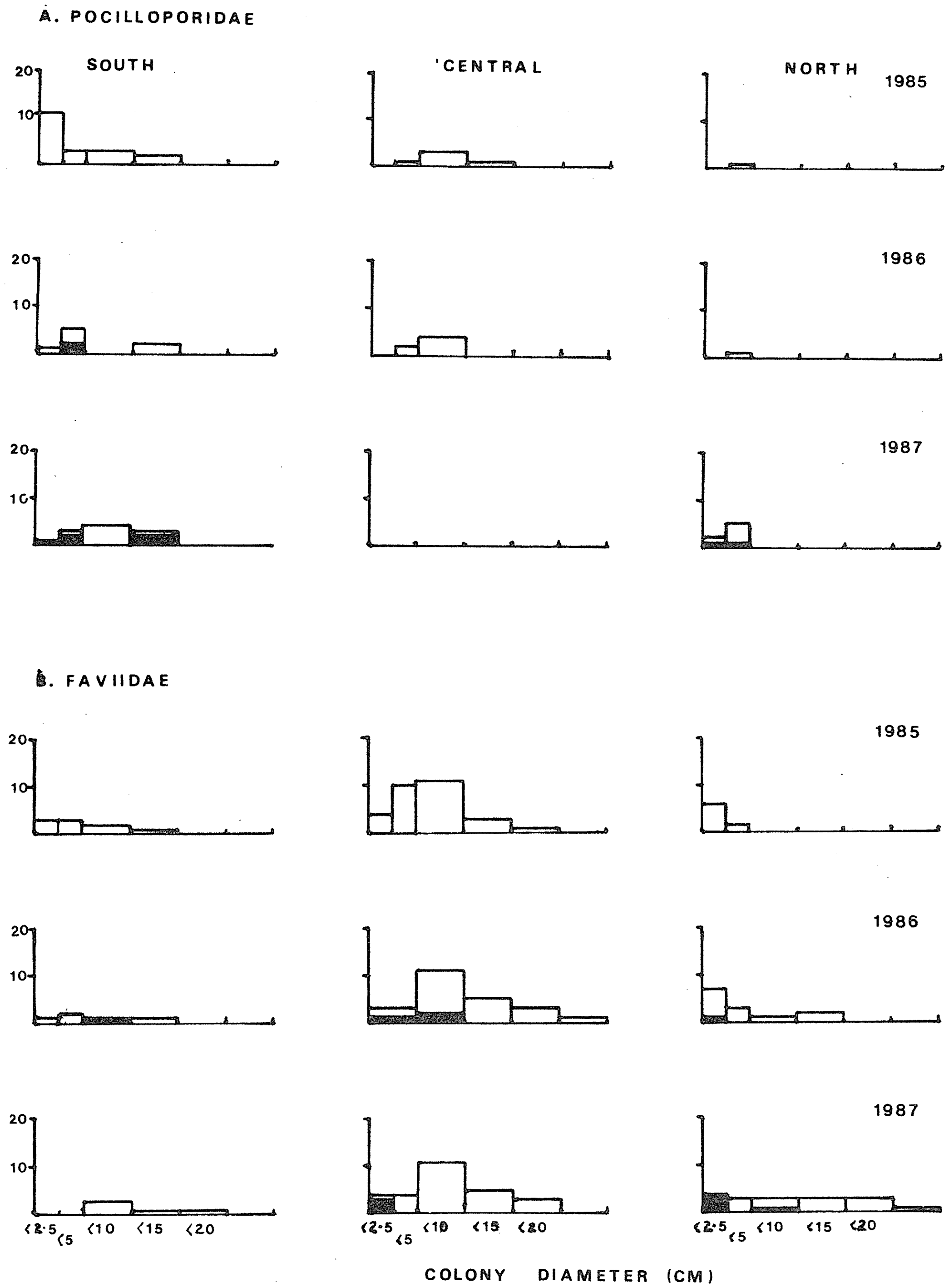
Appendix 3(a). Size frequency distributions of juvenile corals in permanent quadrats, for all coral families pooled. Census periods were approximately one year apart in October/November. The shaded portion of the bar represents the colonies that were less than 2.5 cm in diameter.



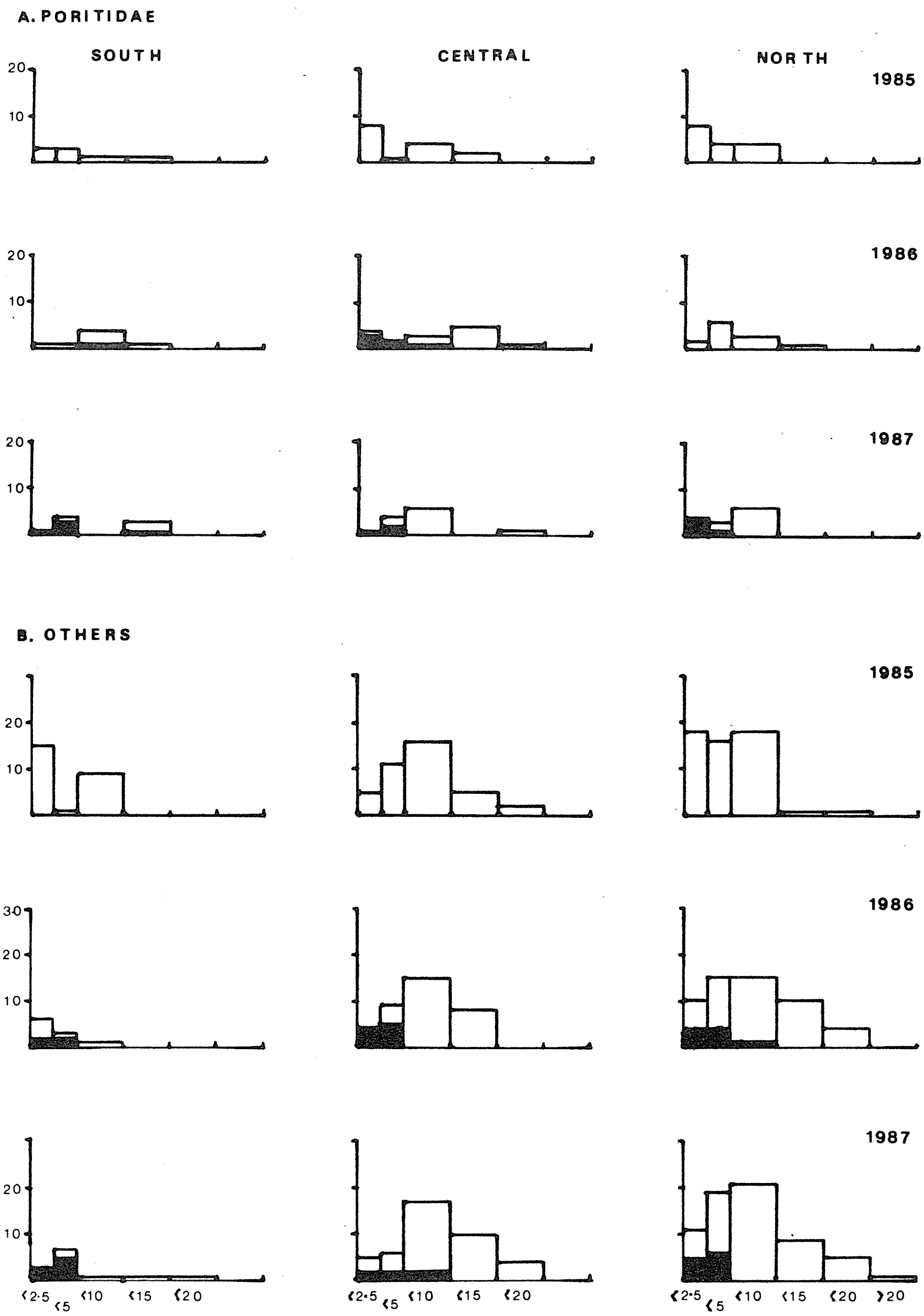
Appendix 3(b). Size frequency distributions of small corals of the genus Acropora in the three zones during the three sample periods. The dark portion of the bar represents the corals that recruited into the quadrats since the previous sample period.



Appendix 3(c). Size frequency distributions of small corals of the genus Montipora in the three zones during the three sample periods. The dark portion of the bar represents the corals that recruited into the quadrats since the previous sample period.



Appendix 3(d). Size frequency distributions of small corals of the families Pocilloporidae (A) and Faviidae (B) in the three zones during the three sample periods. The dark portion of the bar represents the corals that recruited into the quadrats since the previous sample period.



Appendix 3(e). Size frequency distributions of small corals of the family Poritidae (A) and other genera pooled (B) in the three zones during the three sample periods. The dark portion of the bar represents the corals that recruited into the quadrats since the previous sample period.

Appendix 4. Raw data used for size frequency distribution analysis of mean diameters using the combined totals from 2 reefs in each zone.

	Size Class	SOUTH	CENTRAL	NORTH
1985:				
	0-2.5	83	29	60
	2.6-5	89	35	72
	6-10	86	52	59
	11-15	15	15	3
	16-20	15	3	5
	Total	278	134	199
1986:				
	0-2.5	40	16	32
	2.6-5	52	30	69
	6-10	56	45	59
	11-15	16	19	45
	16-20	5	5	5
	Total	169	115	210
1987:				
	0-2.5	17	15	37
	2.6-5	48	27	55
	6-10	70	41	75
	11-15	37	16	31
	16-20	15	12	15
	Total	187	101	213

Appendix 5. Kolmogorov-Smirnoff tests (2-tailed) for changes in size frequency distributions (a) between zones in 1985, 1986, 1987 census years; and (b), between years within each of the zones, ie, comparing size frequencies of colonies between 1986 and 1987 census within each zone. The null hypothesis is that there is no difference in the size frequency distributions in each category at 0.05 significance level. Critical D value calculated by D=1.36 (n1+n2)/n1n2 (Siegel, 1956).

(a) Between Zones:		1985	1986	1987
	D obs.=	0.08	0.1	0.04
South v. Central	D cal.=	0.16	0.16	0.17
	Result=	accept Ho	accept Ho	accept Ho
	D obs.=	0.1	0.11	0.06
Central v. North	D cal.=	0.15	0.16	0.16
	Result=	accept Ho	accept Ho	accept Ho
	D obs.=	0.04	0.12	0.08
South v. North	D cal.=	0.14	0.14	0.14
	Result=	accept Ho	accept Ho	accept Ho

(b) Between Years:		SOUTH	CENTRAL	NORTH
	D obs.=	0.04	0.08	0.19
1985 v. 1986	D cal.=	0.13	0.17	0.13
	Result=	accept Ho	accept Ho	accept Ho
	D obs.=	0.15	0.08	0.07
1986 v. 1987	D cal.=	0.14	0.19	0.13
	Result=	reject Ho	accept Ho	accept Ho

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