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THE RECOVERY PROCESS IN A MECHANICALLY DAMAGED CORAL REEF COMMUNITY: RECRUITMENT AND GROWTH

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ABSTRACT

Coral recruitment and tissue regeneration were studied for 27 months following a freighter grounding on Molasses Reef, Key Largo National Marine Sanctuary (Florida, USA). At the end of the study, hard coral and gorgonian populations in a 1500 m²area of nearly complete destruction were 13% and 10% of pre-impact populations. Recruitment was by species dominant in surrounding communities and was highest in damaged areas that contained surviving adult colonies. Therefore, coral transplantation into heavily damaged areas may increase the rate of recovery. Some transplanted corals should be those displaced by the ship into sand flats. In the two years following displacement these corals showed substantial tissue deterioration. Factors delaying recovery include the presence of fine sediment (material pulverized by the ship) and large amounts of rubble. The removal of such sediment and debris from areas of mechanical impact may enhance recovery by expediting successful recruitment.

INTRODUCTION

Recovery of a coral community following a mechanical disturbance depends on three processes: 1) continued growth of undamaged colonies, 2) continued growth of damaged, but surviving coral colonies, and 3) recolonization of denuded substrates (Endean & Stablum 1973, Endean 1976, Pearson 1981). Recolonization depends on recruitment of coral planulae to the damaged or denuded areas from viable colonies on the reef or from other coral reefs. Regrowth of surviving colonies may also be important to reef recovery (Endean 1971). It has been argued that the greater the number of mature coral colonies surviving an episode of community disturbance, the faster the rate of recovery (Connell 1973, Endean 1976).

Coral spat recruitment and tissue regeneration were studied for 27 months following the grounding of the M/V WELLWOOD, a 122-m freighter, on the upper forereef of Molasses Reef, Key Largo National Marine Sanctuary, Key Largo, Florida. Accounts of the incident and descriptions of damage are given by Curtis (1985) and Gittings & Bright (1988). The contributions of regrowth of damaged tissue and recolonization to community recovery are considered, as is the degree to which location and extent of damage, and substrate conditions affect reef recovery.

METHODS

Random photographic techniques were used to assess hard coral and gorgonian abundance and distribution in heavily and moderately damaged areas of the grounding site (Areas BB and BS, respectively, in figure 1) and in two control areas of comparable depth and topography (Areas XBW and XBE in figure 1). Seventy-two randomly located photos, each providing coverage of 0.5 m² were taken in each area during each quarter between August 1984 (the month of the ship grounding) and November 1986.

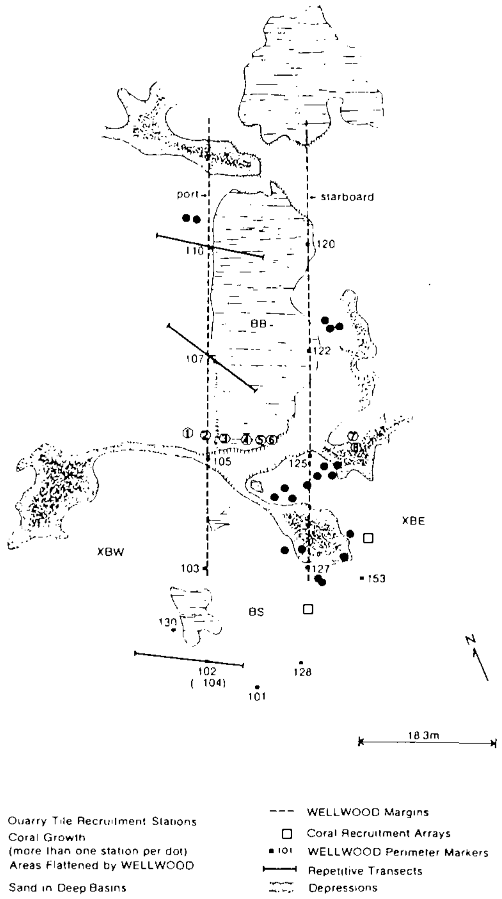

Figure 1. Map of the study area showing each of the study areas and all elements of the study discussed.

The photographs were analyzed to determine sizes and numbers of scleractinians, gorgonaceans, hydrozoans, and zoanthideans by species for each area. Areal cover was considered the vertical projection of a colony downward and was calculated using a Numonics Corp. digital planimeter. For upright gorgonians, relative size was determined ("small" being 0-10 cm height, "medium" 10-30 cm, and "large" over 30 cm).

Repetitive transect photography was used to document time-dependent changes in coral populations at specific sites. Data from three 15 m x 0.5 m transects, established in August 1984 and photographed quarterly through 1986, were taken from the photos as described above. Each transect was established with approximately half its length within the grounding site and half in an area beyond the direct impact of the ship hull (see figure 1).

Eight recruitment stations, each with horizontal, grooved quarry tiles were established along a transect from an unimpacted area west of the grounding site, across the zone of maximal impact, and into an undamaged area east of the site (see figure 1). Tiles were secured approximately 5 cm above the bottom on posts implanted on the reef at each station. Seven stations contained four tiles each. Station 8 had only two tiles due to limited hard substrate availability. Plates were collected at six month intervals (except following a minimal hurricane which destroyed over half the samples; the intact plates had been exposed for only three months). All stations were on hard bottom areas. Stations 7 and 8 were approximately 10 m from Station 6, in a coral community comparable that in Area XBE (see Table 1)

Lateral coral growth over abraded and fractured surfaces of *Montastrea annularis* coral heads was compared with growth on non-damaged heads using repetitive photography. Seventy-eight permanent stations 13.3 x 19.7 cm in area were established on 19 coral heads. Colony borders and polyp mouth positions were traced from quarterly photographs of each station onto mylar drafting material. Images of colony borders from successive photos of each station were then combined. Minor differences in scale were corrected with an image enlarging/reducing map projector. Border lengths and areas of tissue advance and retreat were then measured using a digital planimeter. Rates of areal, linear and net tissue growth and retreat were compared by station, coral head, sample period, and habitat type.

RESULTS

Coral Populations

The characteristics of the four study areas are given in table 1. Results of both regressions and Kruskal-Wallis tests indicated that the number and areal cover of hard corals observed in 0.5 m^2 photographs in the nine quarters sampled did not increase significantly in either of the impacted areas. It is probable, however, that the photographic techniques employed were inadequate for the detection of very small hard corals, which may prefer reef crevices (e.g. Carleton and Sammarco 1987). The gorgonian population, on the other hand, increased significantly ($p<0.01$) in Area BB in the same period. Figure 2 shows that most of the increase was due to the presence of many "small" gorgonians (most were *Pseudopterogorgia americana*). The figure also suggests that some small gorgonians might have grown to "medium" size status (10-30 cm tall) by the end of the study.

Table 1. Approximate areas and some topographic and biotic characteristics of each of the four sample areas of Molasses Reef investigated in this study.

Area	Extent	Characteristics
BB	1500 m^2	Low relief. Nearly completely flattened. Approximately 90% destruction of hard corals and 98% of gorgonians. Part of the upper forereef, adjacent to topreef. Depth approximately 6 m.
BS	850 m^2	Moderate relief. Damage intermittent. Destruction of 42-53% of hard corals and 50-70% of gorgonians. Under stern of ship as it lay aground. Tops of spurs flattened. Numerous toppled and fractured corals. On upper forereef. Depth 6-8 m.
XBE	900 m^2	Low relief. Control area to the east of the grounding site. On deeper portion of upper forereef. Approximately 8.7 scleractinians/m^2 and 10.1 gorgonians/m^2. Depth 6-9 m.
XBW	850 m^2	High relief. Control area to the west of the grounding site. On deepest portion of the topreef. Approximately 9.0 scleratinians/m^2 and 9.2 gorgonians/m^2. Depth 4-6 m.

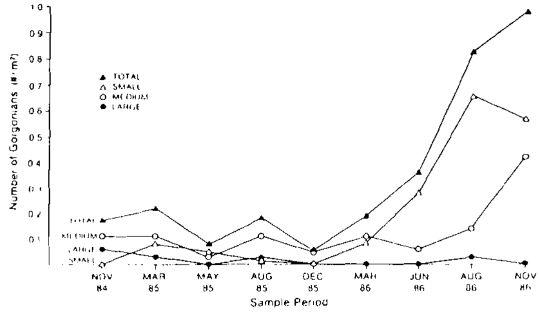

Figure 2. Gorgonian populations in Area BB.

The gorgonian abundance in Area BS, which had been significantly lower than in control areas for the first eight quarters, was statistically indistinguishable from that in control Area XBW during the last period of the study (November 1986). This, however, reflects not only the increase in gorgonian abundance in Area BS, but also a decrease in Area XBW due to the effects of a Hurricane Kate on the area (November 1985).

Neither species richness (the total number of coral species) nor the Shannon-Weaver species diversity index, both of which were depressed in Areas BB and BS by the grounding, changed significantly in any area during the study. Species evenness (species diversity/log of species richness), which describes the apportionment of individuals among species, decreased significantly in Areas BB ($p<0.01$) and BS ($p<0.05$) with time. But the decrease was from levels that were higher than those in control areas immediately after the grounding to comparable levels by November 1986.

Repetitive Transects

The dominant recruiting species on the three repetitive transects were *Pseudopterogorgia* sp. (24 individuals), *Millepora alcicornis* (21), *Favia fragum* (6), *Briareum asbestinum* (5), *Agaricia agaricites* (4), and *Gorgonia ventalina* (4). These also represent the dominant corals of communities in control areas. As suggested by the slopes in figure 3, recruitment was higher on the damaged portion of Transect 102 (in Area BS) than on either Transect 107 or 110 ($p<0.01$, using a Likelihood Ratio Test; Rohatgi 1976). In Area BS, the levels were six times higher for hard corals, and over four times higher for both gorgonians and hydrocorals than in Area BB.

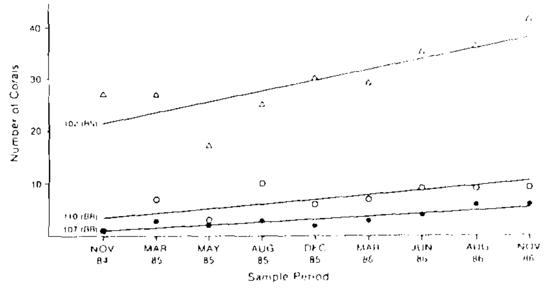

Figure 3. Abundance of corals on the damaged portions of repetitive transects. Regression lines (from least squares regression) are plotted for each transect. All slopes significantly greater than zero.

Furthermore, recruitment on the damaged portion of Transect 102 was higher than on the unimpacted portions of any transect. The relationship is illustrated below (transects underlined together are not significantly different at $\alpha=0.01$; the mean of gross recruitment is given in parentheses in number of new corals/m^2/quarter):

102 Impact	107 Control	102 Control	110 Control	110 Impact	107 Impact
(0.93)	(0.44)	(0.34)	(0.33)	(0.30)	(0.27)

Recruitment may have begun earlier in Area BS than in Area BB. The earliest recruitment observed in Area BS was in March 1985. The extent of bottom surveyed in Area BB was more than twice that in Area BS, but the first recruit there was found in August 1985. Recruitment on control transects was observed as early as March 1985.

Quarry Tile Stations

Fifty-two coral recruits were found on the 100 tiles collected. All were on the grooved undersides of the tiles. Data suggested that there was substantially higher settlement in areas outside the zone of maximal impact (figure 4). Pooling of data by area showed no significant difference between recruitment in Areas XBE and XBW, but significantly lower levels in Area BB ($p<0.0001$, Likelihood Ratio Test). Furthermore, with stations ranked by distance from the center of this zone, a Cox-Stuart Test for trends (Conover 1980) indicated that recruitment decreased significantly with increasing distance from the center of Area BB.

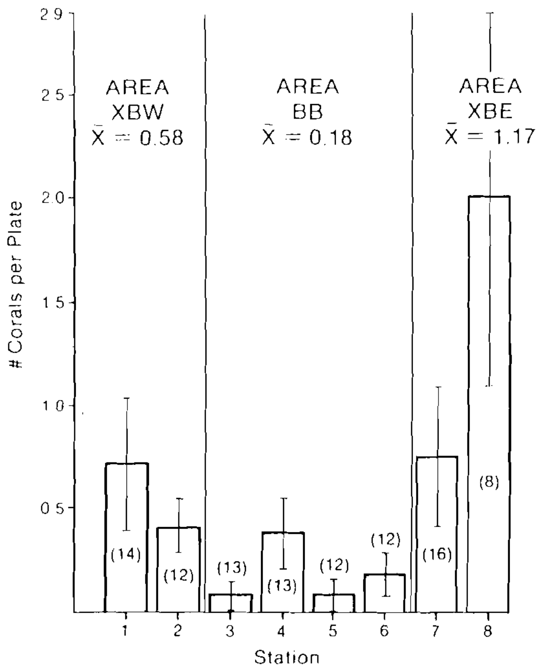

Figure 4. Coral recruitment at each of the quarry tile stations and standard error. Total number of plates is given in parentheses. Variation in number of samples indicate variation in destruction caused by Hurricane Kate.

Coral Growth

Three of the possible effects of a ship grounding on encrusting growth are: 1) changes in growth rates on damaged coral heads, 2) changes in growth on colonies that expelled zooxanthellae (due to shading or mechanical impact), and 3) changes in growth on coral heads displaced into habitats of sub-optimal conditions for growth (e.g. sand flats).

No differences were found in tissue growth or retreat rates on damaged vs. non-damaged coral heads following the grounding. On coral heads exhibiting zooxanthellae loss, growth was less for approximately three months following the grounding ($p<0.05$, Rank Sum Test), but rates of tissue retreat did not increase. Corals displaced into sand flats by the ship as it plowed over the reef had significantly higher rates of tissue retreat than rates of tissue advance throughout the study ($p<0.004$, Sign Test).

That coral tissue deterioration was prevalent on heads displaced into sand can be seen in table 2. On average, over three times as much tissue was lost on coral heads in sand as was gained through tissue growth. Damaged coral heads on the reef and control coral heads had similar amounts of tissue loss and gain.

Figure 5 shows the proportions of advancing, retreating, and stable border tissue on three large coral heads by period. Coral head S (damaged and displaced into sand) had a relatively high proportion of retreating border length during six of the nine

Table 2. Ratio of coral tissue retreat to tissue advance for corals in sand and on the reef.

Period	Months	On Reef	In Sand
A	Aug 84-Nov 84	1.40	8.30
B	Nov 84-Mar 85	0.88	2.92
C	Mar 85-May 85	0.85	1.83
D	May 85-Aug 85	0.71	4.09
E	Aug 85-Dec 85	1.27	3.81
F	Dec 85-Mar 86	0.93	1.60
G	Mar 86-Jun 86	0.92	1.02
H	Jun 86-Aug 86	0.89	8.22
I	Aug 86-Nov 86	0.91	4.18
	Mean	0.94	3.44
	Control Corals	1.08	-

periods, and low proportions of growing or stable border length. Head C (control coral head) generally exhibited similar proportions of advancing, retreating, and stable border lengths, with a tendency toward a slightly higher proportion of advancing tissue along its margins. Head D, a damaged coral head that was not displaced into sand, did not exhibit the period to period stability of the control head (C), but the only period that had a high proportion of retreating margin length was Period A, the first three months following the grounding.

DISCUSSION

The structural damage in Area BB caused by the WELLWOOD, combined with the production of fine sediments by the ship (pulverized reef carbonates), caused a significant loss of habitat complexity (i.e. three-dimensionality). This loss and loose rubble in the area may have delayed the substrate conditioning process (e.g. Crisp and Ryland 1960) and thus successful recruitment in the area (see also Pearson 1974, and Endean 1976).

Ironically, recruitment may have been expedited by the occurrence of Hurricane Kate in November 1985 (a comparatively minor hurricane). It is likely that the hurricane's removal of sediments and loose reef rock from Area BB made the substrate more suitable for successful recolonization (see Pearson 1974). The suitability was likely enhanced in three ways: 1) by limiting the effects of potentially stressful sediment resuspension, 2) through bottom restabilization upon removal of rubble, and 3) by increasing the number of complex microhabitats on the reef.

Hurricane Kate also caused a substantial amount of tissue damage to corals in the area. The ship grounding, however, may also have exacerbated this process. Prior to the storm, there existed a linear pile of rubble on the west side of Area BB that accumulated as the ship plowed over and pivoted on the reef. During the storm, most of the rubble either became waterborne or bounced along the bottom. Direct observations and analysis of photos indicated that a substantial amount of tissue damage was caused by these rubble projectiles. This damage was more extensive in the area immediately adjacent to Area BB than elsewhere. Had the rubble been removed following the grounding, damage to the reef might have been limited to the zones of impact by the vessel.

Hughes (1985) showed an inverse correlation between coral cover and recruitment (see also Opresko 1974 and Grigg 1977). Space availability in experimentally denuded plots, or in coral communities damaged by mechanical disturbances may allow either higher coral settlement or higher early survival. Recruitment data from the area of moderate disturbance in this study support these findings. Differences between recruitment in the two types of damaged areas and in the control area, however, suggest that the presence of nearby mature corals may have enhanced local recruitment in the moderately disturbed area. The results of the quarry tile study suggest a similar conclusion since recruitment was uniformly low at stations in Area BB and higher at all stations outside the impact area.

That coral recruitment was higher in the area of moderate damage than in the area of maximal disturbance during the first year of this study may be due in part to poor substrate conditions in the maximally disturbed area following the grounding. That recruitment was also higher during the second year (i.e. after much of the sediment and rubble was removed by Hurricane Kate from the maximally disturbed area) shows that variability in recruitment exists on spatial scales much smaller than reef tracts, individual reefs (Sammarco and Andrews 1988), or even reef zones (e.g. Wallace and Bull

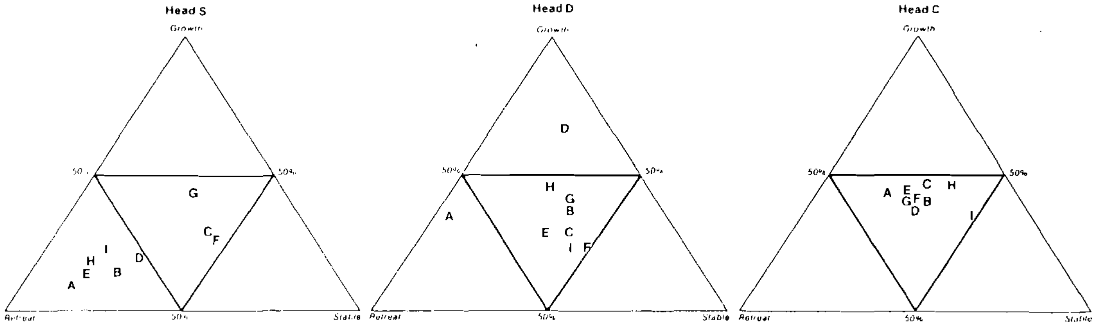

Figure 5. Ternary plots of the proportions of growth, retreat and stability along coral margins for each period (A-I; see table 2 for sample periods). Head S, damaged by the ship grounding, now rests in a large sand flat. Head D is a damaged coral head that rests on the upper forereef. Head C is a control coral head.

1981). As in this study, Baggett and Bright (1985) found variability on a scale of less than 5 m within reef zones. The limited number of coral recruits found in the present study and the relatively short study period, however, preclude the suggestion that differences found are indicators of long-term patterns that can be predicted by the extent of damage to the two damaged areas. Furthermore, it should be noted that other studies (e.g. Fitzhardinge 1985) found no correlation between adult and spat abundance.

Coral growth data strongly suggest that tissue retreat rates were substantially higher on coral heads displaced into sand-filled depressions than on coral heads remaining on hard substrates. Retreat areas on coral heads in sand exceeded growth areas by a factor of 3.44. If this ratio remains at this level, several of the heads examined may continue to deteriorate over the next several years and will probably lose most or all living tissue.

The results of this study may be applicable to coral reef management practices, both in minimizing secondary damage and in increasing the rate of recovery of a reef following mechanical disturbance. First, the removal of fine sediments following a ship grounding would increase the microtopographic complexity of impacted areas. This might also decrease the time between the disturbance and the first successful recruitment (i.e. substrate "conditioning" time). Presumably, the sooner this removal takes place, the sooner the substrate becomes conditioned for recruitment.

Removal of rubble accumulations after mechanical disturbance would serve two purposes. First, secondary damage caused by storm-tossed rubble would be minimized. Secondly, removal would limit the destruction of recently settled corals within the site. This practice was also recommended by Endean & Stablum (1973) following *Acanthaster planci* devastation and by Wulff (1984) following dredging activities.

The differences found in recruitment rates, as they related to proximity to adult corals, suggest that coral transplantation might be a viable remedial measure for increasing the recovery rate of a denuded area. Transplantation was also recommended by Maragos (1974) and Gabrie et al. (1985) for dredged areas, and by Alcala et al. (1982) and Auberson (1982) for blast fishing areas. Transplantation of sexually mature colonies might increase not only the potential for recruitment, but also the habitat complexity essential to full recovery of a reef community, and would also be of aesthetic value (Shinn 1976). Furthermore, Maragos (1974) and Auberson (1982) showed that sediments may have less of an effect on the survival of transplants than on the survival of recruits.

It might be advisable to transplant large fragments of corals that had been displaced into sand flats. Data showed that coral tissue on these colonies will, most likely, otherwise continue to deteriorate. Removing these colonies from sand flats and affixing them to the reef may stop excessive tissue deterioration.

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