FIVE YEARS OF CORAL RECOVERY FOLLOWING A FREIGHTER GROUNDING IN THE FLORIDA KEYS

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Coral community recovery has been followed for five years since the destruction of a portion of Molasses Reef, Key Largo National Marine Sanctuary, by a 122 meter freighter, which ran aground in August 1984. Underwater repetitive and random photographic methods, visual counts, and artificial substrates were used between 1984 and 1989 to assess coral populations, cover, recruitment, and the fate of coral colonies damaged by the grounding. We report here on data and results from random photographic methods and underwater visual censuses. Coral abundances had redeveloped in 1989 from virtually 0% in an area of major impact to a level approximating 65-78% of supposed pre-impact populations though colonies were very small. Cover of hard corals in 1989 was 22% of pre-impact cover, and gorgonian cover approximately 40% of pre-impact cover and tend to have high rates of recruitment. Coral recruitment has been dominated by species which brood larvae. These species are also numerical dominants in mature surrounding communities. Though recovery would occur naturally over an extended period of time, transplantation could be used as a way to increase the relative abundance of species which only rarely have been found as coral recruits. These include primarily the large massive corals conspicuous in typical mature reef communities. Most of these species are broadcast spawners, which have long planktonic stages, low recruitment rates, and low relative abundances in mature communities. Transplantation also restores the habitat complexity essential to the development of the associated invertebrate and fish assemblages characteristic of these diverse ecosystems.

INTRODUCTION

In the early morning of 4 August 1984, the 122 m freighter M/V Wellwood ran aground on Molasses Reef, near the southern boundary of the Key Largo National Marine Sanctuary (Figure 1). The damage caused by the grounding was documented by Bright and Andryszak (1984), and Curtis (1985). Some coral population recovery over a 27 month period following the grounding was reported by Bright *et al.* (1987), Gittings and Bright (1988), Gittings (1988) and Gittings *et al.* (1988). Gittings and Bright (1988) reported three categories of mechanical damage on Molasses Reef: damage caused by initial contact, damage by the grounding itself, and damage during ship salvage. In the area of initial ship contact (approximately 8 m depth), large corals along the inbound path protruding substantially above the bottom were abraded, toppled or fractured (within and near Area BS in Figure 2). The *grounding site* itself (6-8 m depth) was the most heavily impacted portion of the reef. In the area under the bow and amidships (Area BB in Figure 2), the broad tops of forereef spurs were ground flat by the ship hull, and linear piles of boulders were formed by the plowing of the port side of the ship as it pivoted on the reef. Nearly all corals were destroyed in an area approximately 1500 m^2 which was flattened by the ship. Many corals in depressions survived, but were shaded during the 12 days the ship remained aground, and lost zooxanthellae (symbiotic algae necessary for vigorous growth). This also occurred in corals toppled during the grounding. Significant tissue loss and some mortality occurred as a result of this "bleaching". During *ship salvage,* many corals and large barrel sponges seaward of the grounding site were damaged by tug cables used to pull the vessel off the reef (especially in Area C in Figure 2).

The information presented here represents a portion of work conducted between 1984 and 1989 on coral community assessments at Molasses Reef. Though data were collected from four areas of the accident site between 1984 and 1986 (two damage and two control areas), data presented here are from coral populations in only two areas (one damaged and one undamaged), since the other areas were not sampled after 1986. Also, we present data from underwater counts of small individual corals in square meter quadrats in an area denuded by the grounding.

METHODS

Field sampling took place quarterly between August 1984 and November 1986, then again in September 1988 and August 1989. During 1988 and 1989, coral population level assessments were made in only two of the four areas sampled in 1984-1986. These were in the area most heavily impacted by the grounding (Area BB in Figure 2) and in one control area (Area XBE). Based on topographic characteristics, depth ranges, and preliminary recovery data, Gittings (1988) suggested that these two areas may have had similar pre-impact coral communities and may eventually have similar communities after recovery.

Random photographic techniques were used to assess hard coral and gorgonian abundance and distribution in Areas BB and XBE. Seventy-two randomly located photos were taken in each area, each providing coverage of 0.5 m^2. They 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 onto the substrate (like canopy cover in terrestrial ecosystems) and was calculated using a digital planimeter. For upright gorgonians, relative size was determined ("small" being 0-10 cm height, "medium" 10-30 cm, and "large" over 30 cm).

To obtain percent cover estimates which included information on gorgonian corals, measurements of percent cover were also made using a point-intercept technique. Clear acetate overlays containing 100 randomly located points were laid over photographs. Colonies under each point were counted. The total number of points occupied by each group (hard corals or gorgonians) on a photograph represented one estimate of percent cover.

Recruitment was assessed from random photographic data making underwater counts of juvenile corals in Area BB. Numerical abundances on random photographs were compared between sampling periods. Recruitment rates were determined in terms of net increases in individual groups (gorgonians, scleractinians, and hydrozoans) and species, where possible. In November 1986, September 1988, and August 1989, underwater counts in 1 m^2 quadrats were made in Area BB to determine the population of recently settled corals in the area. During each of these periods, scleractinians, gorgonians, hydrozoans, zoanthideans, and selected associated invertebrates were counted in 18 quadrats. Samples were spaced approximately 1 m apart on a line from the southernmost to the northernmost portion of Area BB. The substrate was visually inspected, spending approximately five minutes per quadrat searching for and enumerating the inhabitants. This visual method was employed because some juvenile corals are found predominantly on the undersides or sides of reef surfaces, and may not be accounted for using down-looking photographic techniques.

RESULTS

Figures 3 and 4 compare abundances of scleractinian and gorgonian corals in Areas BB and XBE from 1984 to 1989 (confidence intervals are not displayed on figures, since they are reflected in multiple range groupings below). For hard corals, statistical analyses indicate significant differences between time periods in Area BB, but no significant differences between periods for Area XBE. Differences in Area BB are illustrated below (sample periods underlined together are Tukey multiple range test groupings which are not significantly different at $P = 0.05$ *using a Kruskal-Wallis Test; abundance increases from left to right):*

Hard Coral Populations in Area BB: F = 30.61, p < 0.0001

Dec	Nov	May	Mar	Mar	Nov	Aug	Jun	Aug	Sep	Aug
85	84	85	86	85	86	86	86	85	88	89

Tukey groupings below reflect the fairly consistent increase in gorgonian population levels with time:

Gorgonian Coral Populations in Area BB: $F = 110.58$, $p < 0.0001$

Dec	May	Mar	Nov	Mar	Aug	Jun	Aug	Nov	Sep	Aug
85	85	85	84	86	85	86	86	86	88	89

Bright *et al.* (1987) and Gittings (1988) showed that population levels in Area BB had not recovered by November 1986. Though coral population levels increased significantly with time in Area BB after 1986, they were still statistically distinguishable from those of Area XBE for both scleractinian and gorgonian corals in 1989. That is, scleractinian and gorgonian coral populations were still significantly lower in Area BB.

Figure 5 compares the numerical abundance of scleractinians, gorgonians, and all hard corals combined (scleractinians plus *Millepora* spp.) relative to populations of these groups in Area XBE. The data suggest population recovery of some 78% for scleractinians, 57% for all hard corals, and 65% for gorgonians.

Percent cover of hard corals, gorgonian corals, and total coral cover all were significantly lower in Area BB than XBE during all sampling periods between 1984 and 1989 ($p < 0.0001$). Within Area BB, however, percent cover increased significantly with time for all three groups, especially after 1986. Tukey groupings of sample periods are given below for each group (percent cover increases left to right, except in cases when certain months had to be reversed due to multiple range test pairings):

Hard Coral Cover in Area BB: $F = 8.93$, $p < 0.0001$

Nov	May	Dec	Nov	Mar	Jun	Mar	Aug	Aug	Sep	Aug
84	85	85	86	86	86	85	86	85	88	89

Gorgonian Coral Cover in Area BB: $F = 107.54$, $p < 0.0001$

May	Mar	Dec	Jun	Aug	Mar	Nov	Aug	Nov	Sep	Aug
85	86	85	86	85	85	84	86	86	88	89

Total Coral Cover in Area BB: $F = 60.48$, $p < 0.0001$

May	Dec	Mar	Nov	Jun	Mar	Aug	Nov	Aug	Sep	Aug
85	85	86	84	86	85	85	86	86	88	89

Gorgonian cover increased from virtually 0% of that in Area XBE early in the study to approximately 40% of cover in Area XBE by August 1989 (Figure 6). Hard coral cover has increased from an average of 12.4% of cover in Area XBE during the initial 27 month study to 22.1% in 1988 and 1989.

The abundances of small, medium, and large gorgonians for Areas BB and XBE (Figures 7 and 8) indicate a disproportionately low population of large gorgonians in Area BB. Small and medium gorgonians, however, dominated in both areas. The paucity of large specimens reflects the lack of age class structure recovery, even though numerical populations probably approximate 65% of pre-impact levels.

Table 1 shows the abundance of various taxa in 18 quadrats in which underwater counts were made by a diver during 1986, 1988, and 1989. These quadrats were located along transects in Area BB, and were in the same general location, but were not repetitively sampled. Scleractinian and gorgonian data show a gradual and significant increase in coral populations in Area BB between 1986 and 1989, which is consistent with data from other elements of the study. The total number of corals in 1989 was approximately $20.8/m^2$, with gorgonians and scleractinians having approximately equal populations (nearly $10/m^2$ each), and accounting for nearly 95% of all corals with *Millepora* spp. representing 5%. There has been little change in *Millepora* sp. abundance. Note that scleractinian population estimates made by visual censuses were approximately twice as high as those made using random photographic techniques. Gorgonian population estimates were nearly the same using both techniques (compare data in Table 1 and Figure 3). This reflects the preference of juvenile hard corals for the sides and undersides of reef surfaces in shallow water rather than surfaces exposed to direct sunlight (e.g. Lewis, 1974). Apparently, young gorgonians do not exhibit such a preference.

Stony coral recruitment that occurred over the first five years of recovery was dominated numerically by *Favia fragum, Agaricia agaricites, Porites* sp., and *Millepora alcicornis*. Along with *Pseudopterogorgia* spp. the dominant gorgonians, these species accounted for 90% of all corals in the area in 1989 (Table 1). Nevertheless, the number of coral species represented in the samples has also increased gradually. This is due primarily to the increase in richness of the scleractinian fauna. The number of gorgonian species observed has apparently decreased with time.

Among the dominant hard corals, *Favia* in particular represented a significantly higher proportion of the numerical population in Area BB than in Area XBE in 1988 and 1989 (18-25% vs. 2-3%, as estimated from random photographs). More equal relative abundances were found in these areas through 1986 (Gittings, 1988). *Favia fragum* abundance remained constant between 1984 and 1986, increased significantly after 1986, then increased again between 1988 and 1989 ($F = 30.40$, $p < 0.0001$; using Kruskal-Wallis Test and Tukey Multiple Range Test groupings).

Millepora spp., on the other hand, represented only 16-18% of all reef corals on random photos in Area BB during 1988 and 1989 and 37-45% in Area XBE. During the initial study, *Millepora* sp. represented over 40% of the population in Area BB, which was comparable to other areas. The increase in the number of Favia colonies resulted in the decreased relative abundance of *Millepora*. Though significant differences in *Millepora* spp. populations occurred between periods ($F = 4.97$, $p < 0.0001$), no long-term increase was observed.

The relative abundance of *Porites* spp. also increased from 1988 to 1989 in Area BB (from 6 to 21%). Population density also increased after 1988 ($F = 24.05$, $p < 0.0001$). In 1984-1988 samples, these corals represented 1-6% of hard corals in Area BB and population levels had been similar ($p > 0.05$). They have consistently represented 8-10% in Area XBE.

Agaricia populations remained stable in Area BB through 1986 ($p > 0.05$). Significant increases occurred between 1986 and 1988, and between 1988 and 1989 ($F = 17.30$, $p < 0.0001$). Relative abundance in Area BB increased from approximately 9% of hard corals during 1984-1986 to 14% in 1988 and 18% in 1989. Relative abundance of *Agaricia* in Area XBE has remained between 18 and 25% since the grounding.

Generally speaking, the massive corals such as *Montastraea* spp., *Diploria* spp., and *Dichocoenia stokesi*, which were conspicuous in surrounding habitats, were only rarely encountered in Area BB. Their relative abundances, however, were similar in both areas. Therefore, though conspicuous due to their larger size in undisturbed habitats, these corals do not represent numerically dominant species in any area.

The 1988-89 data indicate that gorgonian recruitment in Area BB was dominated by *Pseudopterogorgia* spp. Most of these were *P. americana*, which represented 71-81% of all gorgonians in Area XBE. Until 1989, this relative abundance also occurred in Area BB. In 1989, however, the proportion of *Pseudopterogorgia* in Area BB was 91%, suggesting significant recent recruitment relative to other gorgonian species. *Pseudopterogorgia* abundance began to increase significantly after June 1986, then continued between 1986 and 1988 and between 1988 and 1989 ($F = 111.30$, $p < 0.0001$).

Conspicuously absent or rare species in Area BB in 1989 included *Briareum asbestinum* and *Gorgonia ventalina*. *B. asbestinum* was not found in Area BB in 1989, even though it represented 8.1% of gorgonians in Area BB during the initial study, and averaged 11-14% of gorgonians in Area XBE over the entire study period. No significant differences were found between sample periods for this species ($F = 0.88$, $p < 0.55$). A low relative abundance of *G. ventalina* might be expected in Area BB, since values in Area XBE averaged between 1 and 3% over the study period. In 1988, however, the relative abundance of *G. ventalina* in Area BB was 24%. The absolute abundance was four times higher than in 1989 (significant differences; $F = 21.63$, $p < 0.0001$). In fact, population levels in September 1988 were significantly higher for *G. ventalina* in Area BB than all other sample periods.

DISCUSSION

The Status of Reef Recovery

By the end of the summer of 1989, estimated scleractinian abundance in Area BB was approximately 78% of that in control Area XBE, and gorgonian abundance was 65% of that in the control area. These levels are higher than would have been predicted from extrapolation of data collected between 1984 and 1986 (see Gittings, 1988). This is because recruitment rates have increased with time. Figure 9 shows a curve that accounts for much of the variability in the population data (a second order polynomial) in Area BB ($r^2 = 0.975$). Extrapolation of these data would suggest numerical population recovery at a time approximating six years following the grounding. When such a model is applied to individual groups, complete scleractinian population recovery would be predicted at 65 months and gorgonian population recovery at 72 months. We are currently in the process of developing a model that more accurately reflects natural conditions than the polynomial applied. However, initial evaluations suggest that the polynomial curve estimates are fairly accurate over the time periods involved in this study. For example, complete numerical recovery is estimated at approximately 80-85 months for total corals for the model being developed as opposed to 70 months by the polynomial. This is because recruitment rates are expected to decrease as the carrying capacity of the habitat is approached, a factor not accounted for by the polynomial.

A similar evaluation of percent cover suggests average recovery through 1989 of some 35% for all corals (40% for gorgonians, and 22% for hard corals). As recruitment rates currently appear to be increasing with time, and as areal cover of individual colonies increases as the square of colony radius, the percent cover recovery rate should also increase with time.

As suggested by the percent recovery estimates given above, however, gorgonian corals, which grow much faster in area than stony corals, have contributed most significantly to the recovery of cover on the reef. Percent cover of gorgonians, therefore, would be expected to approach control levels much faster than stony coral cover. Extrapolation of best fit curves on percent cover data suggest that, if recovery continues to increase at a rate comparable to rate increases between 1984 and 1989, control community percent cover could be reached in Area BB at approximately seven years for gorgonians ($r^2 = 0.965$), and 12.5 years for hard corals ($r^2 = 0.192$).

Nevertheless, several other community characteristics must also develop in addition to numerical population and percent cover recovery in Area BB before community recovery can considered complete. These include, but may not be limited to, recovery of an age class structure similar to that of control areas, development of three-dimensional habitat structure in the area comparable to that in control areas, and development of a diverse community of associated reef algae, reef invertebrates and fishes.

Species dominating the recovery community in Area BB are the same as those dominating mature communities in areas surrounding the grounding site. However, relative abundances changed considerably over the course of the study. The scleractinian coral species dominating Area BB (*Favia fragum, Porites* sp., and *Agaricia agaricites*) have been described by van Moorsel (1983) and Szmant (1986) as having reproductive strategies involving larval brooding rather than gamete broadcasting and external larval development. Planulae released from brooding adults are able to settle soon after release and may colonize areas near parent colonies. This strategy is characteristic of species with small colony size, multiple reproductive cycles per year, and high recruitment rates, and are generally species in unstable habitats. They are analogous to r-selected, opportunistic species in some respects (Pianka, 1970), especially in their ability to colonize substrates made available through removal of other organisms, as occurred during the ship grounding. Thus, a high relative abundance of these species in the early recovery community should be expected.

On the other hand, species occurring in surrounding habitats that broadcast gametes, such as *Montastraea annularis, M. cavernosa, Diploria strigosa, Acropora* spp., and *Siderastrea siderea* might be expected to colonize Area BB at a much slower rate and reach maximum abundance in a more mature recovery community. These species have, until now, been found only occasionally in Area BB. Such species generally occur as larger colonies than brooding species, and adults have only one spawning period per year (Szmant, 1986). They become conspicuous in mature communities due to their size, and contribute substantially to coral cover on the reef, but may not be numerical dominants.

For gorgonian corals, there appears to have been a recent shift in the community in Area BB to a more monospecific assemblage, dominated by *Pseudopterogorgia* sp. (predominantly *P. americana*). Unfortunately, very little is known about gorgonian reproductive strategies (Brazeau and Lasker, 1989), making recovery patterns difficult to interpret. Unlike most scleractinian species, most gorgonians are thought to contain separate sexes, have internal fertilization, and brood larvae. The known brooding species include *Briareum asbestinum, Eunicella singularis, E. stricta, Muricea californica,* and *M. fruticosa* (see references in summary table in Brazeau and Lasker, 1989). *Pseudopterogorgia bipinnata*, which occurs on Molasses Reef and is a congener of the most abundant species in the recovery community in Area BB (*P. americana*) is a broadcasting species. The abundance of *Pseudopterogorgia* colonies in Area BB, however, and the dominance of these species in surrounding habitats, suggests that these species are probably brooders and parent colonies are local.

Implications for Amelioration

The study conducted over the first 27 months following the WELLWOOD grounding resulted in a number of suggestions for potential ameliorative measures that might minimize secondary damage and enhance recovery following mechanical disturbance to reef communities. These measures included fine sediment removal, rubble removal, and coral transplantation into denuded areas. Sediment removal can enhance recruitment and can increase habitat complexity (Gittings *et al.*, 1988). Rubble removal reduces secondary damage caused by resuspension during storms and increases bottom stability (Endean and Stablum, 1973; Wulff, 1984; Gittings, 1988). Coral transplantation may increase recruitment in denuded areas (Gittings *et al.*, 1988), increases habitat complexity (Maragos, 1974; Gabrie *et al.*, 1985), and has aesthetic value (Shinn, 1976).

Recruitment data suggest that coral reproductive strategies should be considered in decisions regarding species to be included in a transplantation program. It is apparent that a number of species quite naturally become abundant in very few years in denuded habitats (e.g. *Agaricia* spp., *Favia fragum*, and *Porites* spp., *Pseudopterogorgia* sp.). At least for scleractinians, young colonies of these species probably arise from brooded planulae from local populations. Furthermore, these species tend to be small and abundant rather than large and conspicuous. In fact, large colonies tend to be much less abundant. Therefore, it makes little sense to include most brooding species in a transplantation program.

Corals that might be considered for transplantation should be chosen from large, massive broadcasters, which on Molasses Reef include *Montastraea annularis, M. cavernosa, Diploria strigosa, Siderastrea siderea*, and possibly *Acropora* spp., among others. These corals generally broadcast gametes into the water column, where fertilization takes place, and dispersal is often over long distances (Szmant, 1986). Successful recruitment is fortuitous and larval mortality high, but survival of colonies, once a safe size is reached, can be high. As with all massive corals, these species are slow growing (excepting *Acropora* spp.). Because such species are usually found in mature communities as large colonies in relatively low abundance, these types of species would be the best candidates for reef restoration. It should be recognized, however, that even without transplantation, these species occurred in 1989 in relative abundance comparable to the control area. They would, therefore, be expected to recover naturally over a long period of time to the pre-impact age class structure. But the chances for natural recruitment into any restricted area for these species are low, and natural recovery time can, therefore, be considerable. Furthermore, while transplantation offers the community sexually reproductive individuals, more importantly it provides the habitat complexity necessary for recovery of the full complement of reef invertebrates and fishes that characterize these diverse assemblages.

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Table 1.. Quadrat counts made underwater by a diver in 1986, 1988, and 1989. Visual counts of Scleractinia, and other conspicuous taxa were made in eighteen 1-m2 quadrats during each year.

Taxa	Nov 1986 (#/m²)	Sep 1988 (#/m²)	Aug 1989 (#/m²)
Scleractinia			
Acropora cervicornis	-	0.06	0.06
Agaricia sp.	0.28	1.17	2.22
Dichocoenia sp.	-	-	0.22
Diploria strigosa	-	-	0.06
Diploria labyrinthiformis	-	-	0.11
Diploria sp.	0.11	0.11	-
Eusmilia sp.	0.06	-	-
Favia fragum	0.44	1.00	2.17
Montastraea annularis	-	0.06	-
Montastraea cavernosa	0.11	0.33	0.39
Mussa? sp.	-	-	0.17
Porites sp.	0.33	1.72	4.22
Siderastrea siderea	-	-	0.17
Siderastrea radians	-	-	0.06
Siderastrea spp.	-	0.22	-
Stephanocoenia michelini	-	-	0.11
Total Scleractinia	1.33	4.67	9.94
Std. Error	0.35	0.62	1.09
Gorgonacea			
Briareum asbestinum	0.06	0.06	-
Gorgonia ventalina	0.06	0.28	0.67
Plexaura sp.	-	0.06	-
Plexaurella sp.	0.06	-	-
Pseudopterogorgia spp.	1.39	4.72	9.11
Pterogorgia citrina	0.06	-	-
Total Gorgonacea	1.61	5.11	9.78
Std. Error	0.30	0.97	1.15
Hydrocorallina			
Millepora spp.	0.83	1.28	1.06
Std. Error	0.25	0.30	0.27
Total Corals	3.78	11.06	20.78
Std. Error	0.59	1.10	1.45
Total Coral Taxa	12	13	15

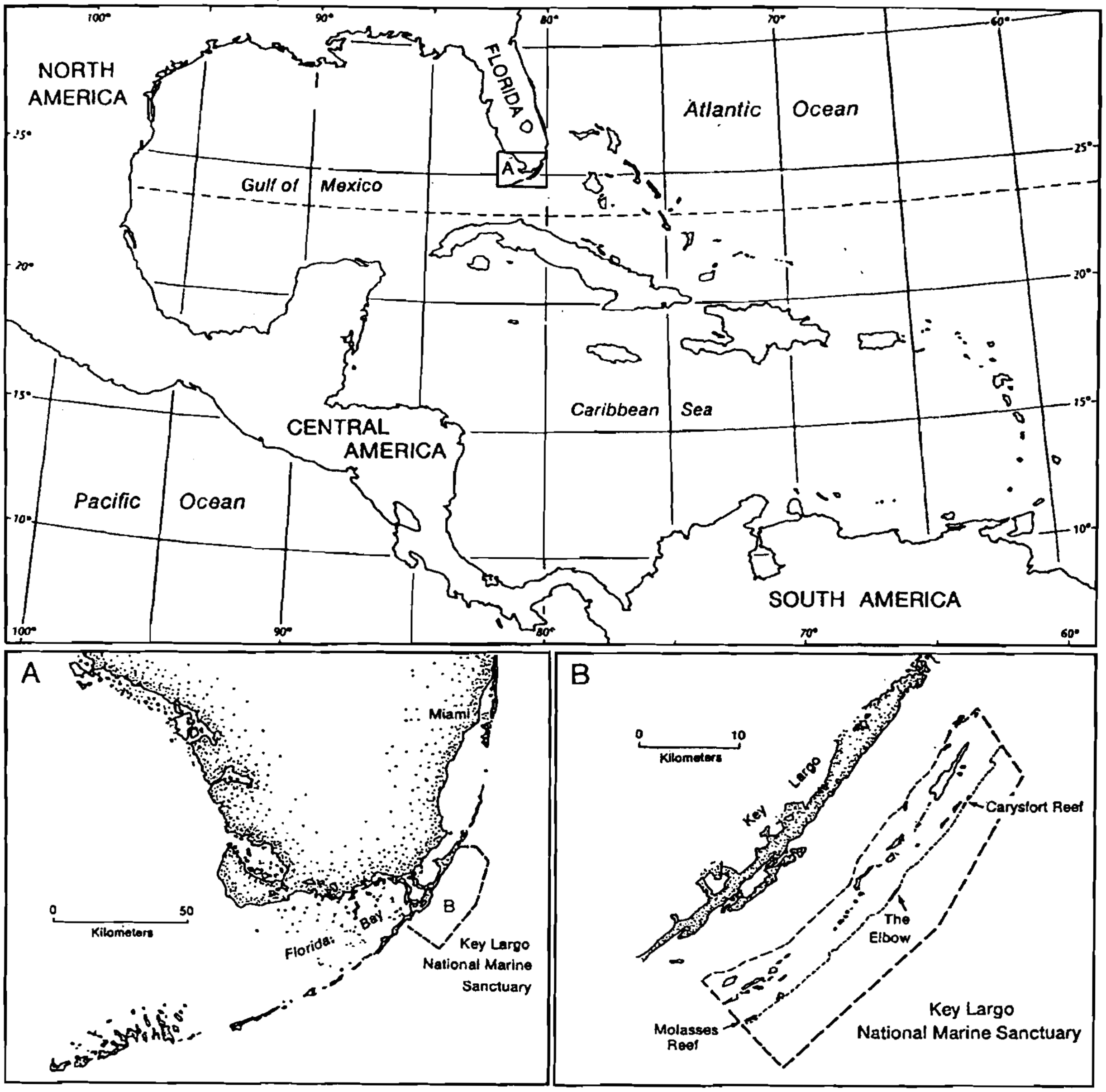

Figure 1. Chart of the Caribbean Sea and Gulf of Mexico showing the locations of the Florida Keys (A), the Key Largo National Marine Sanctuary (B), and Molasses Reef.

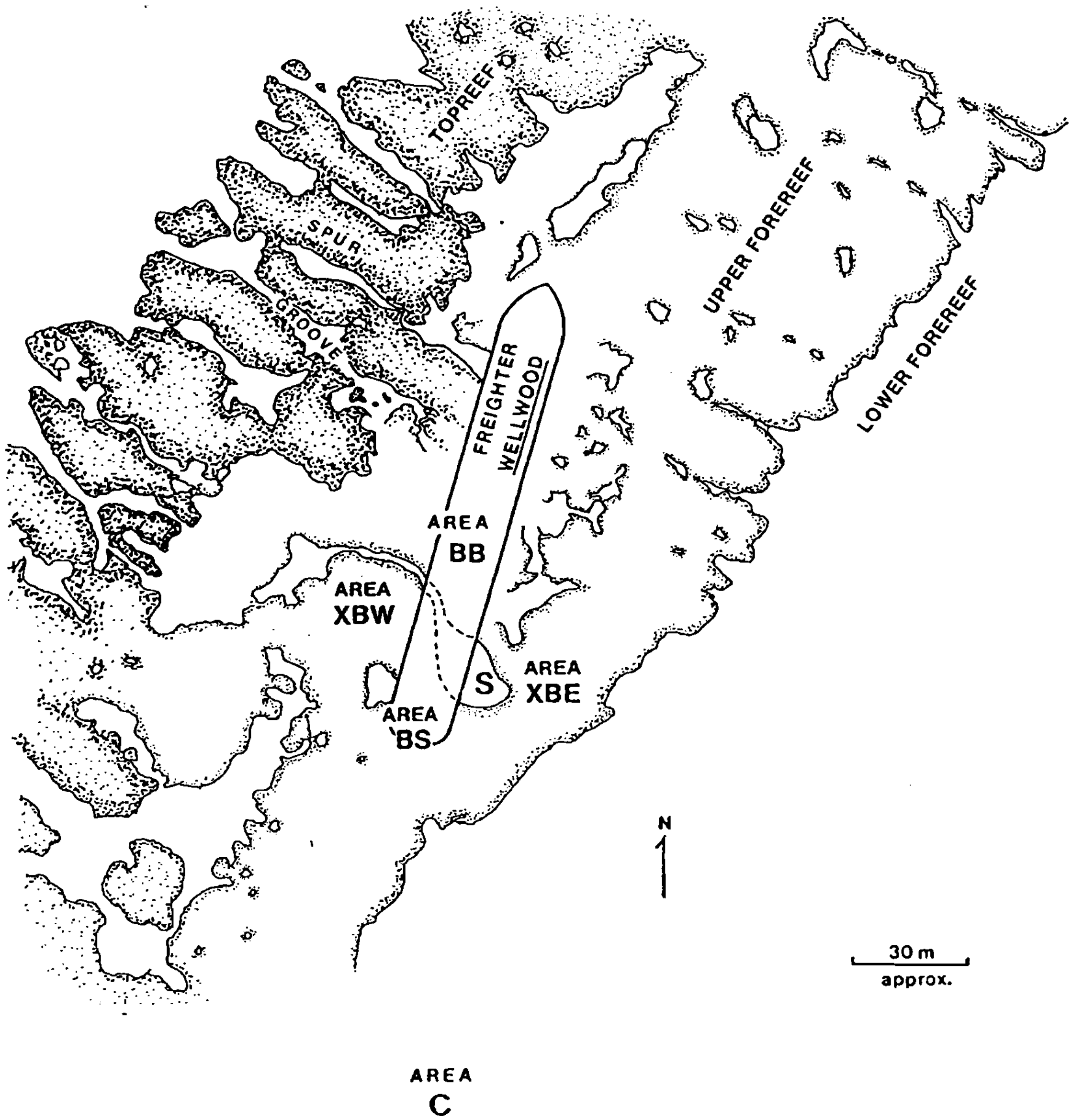

Figure 2. Locations of the freighter WELLWOOD, hard aground between 4 and 16 August 1984, on the upper forereef of Molasses Reef, Key Largo National Marine Sanctuary (shallow water to the northwest, deeper water to the southeast).

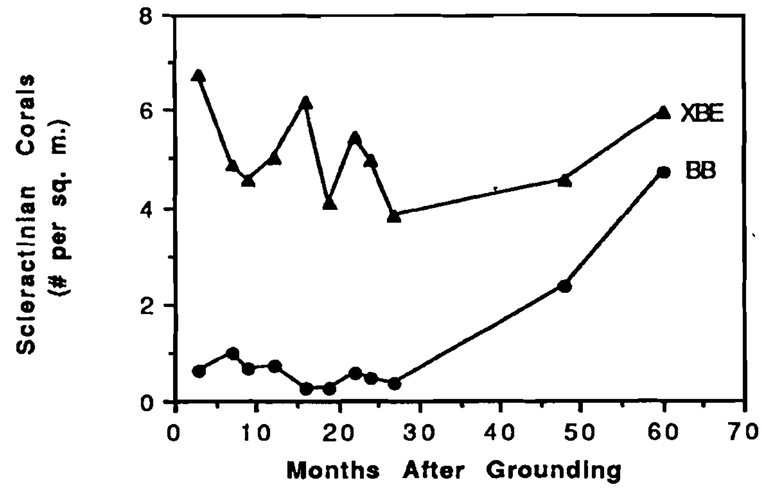

Figure 3. Scleractinian coral population in Areas BB and XBE between November 1984 (three months following the grounding) and August 1989 (month 60) as estimated using random photography.

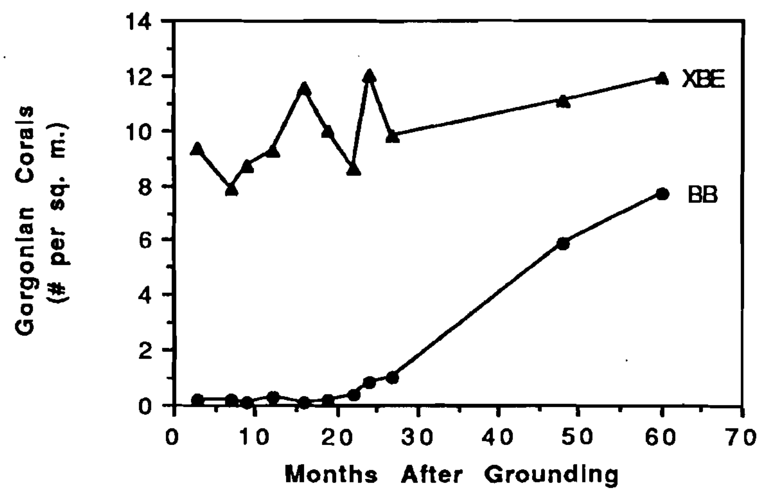

Figure 4. Gorgonian coral population in Areas BB and XBE between November 1984 (three months following the grounding) and August 1989 (month 60) as estimated using random photography.

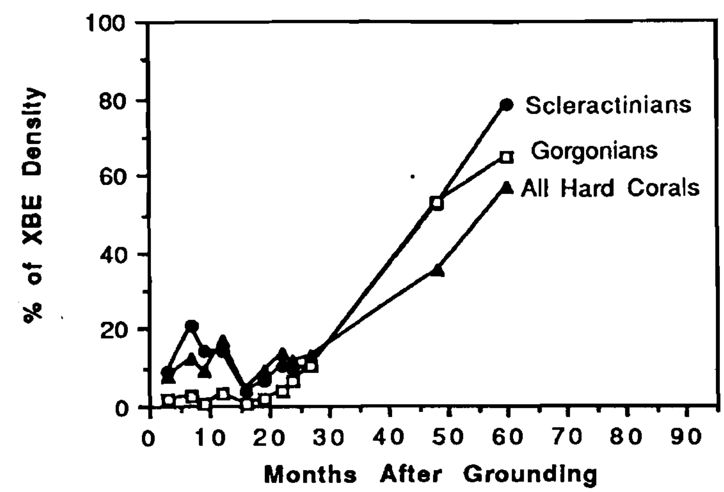

Figure 5. Populations of scleractinians, all hard corals combined (i.e., including Millepora spp.), and gorgonians in Area BB, expressed as percent of corresponding population in Area XBE for the five years since the grounding.

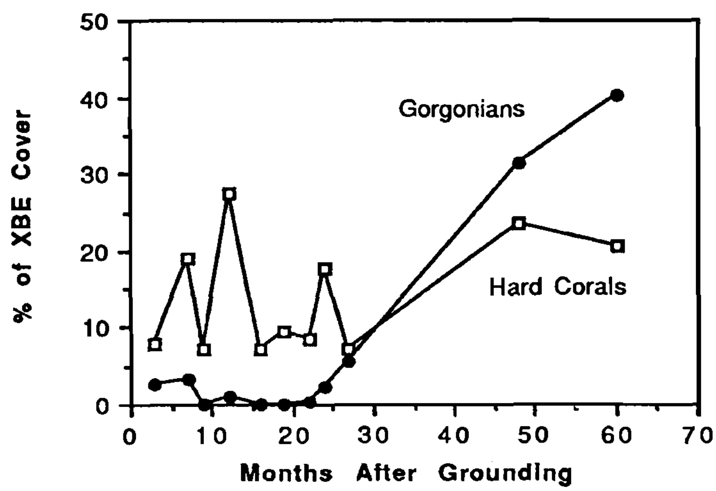

Figure 6. Percent cover of gorgonians and stony corals in Area BB between 1984 and 1989, expressed as percent of corresponding cover in Area XBE.

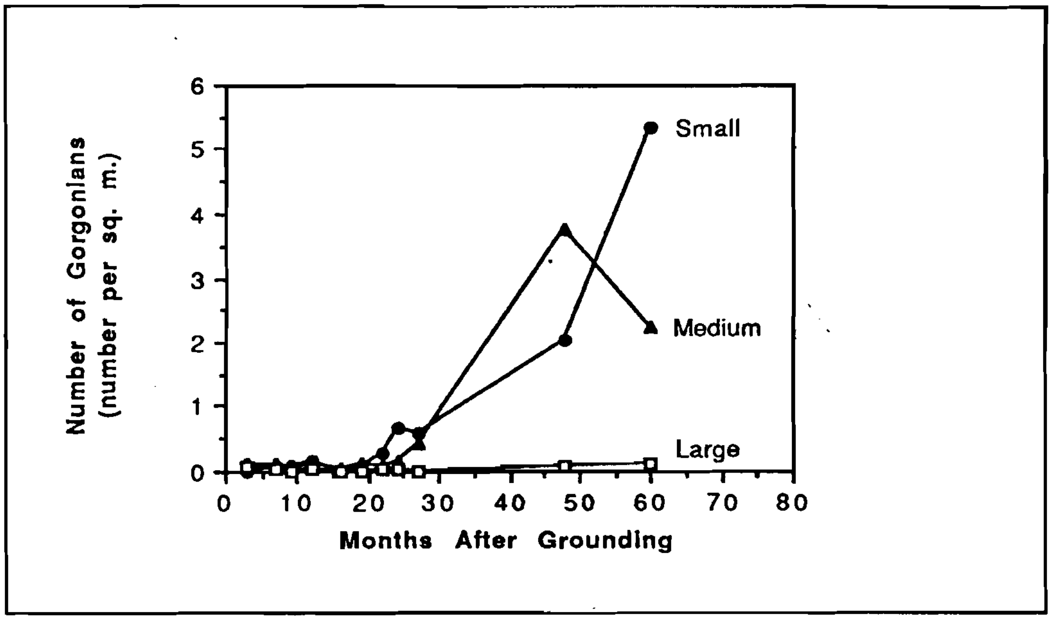

Figure 7. Density of "small" (0–10 cm tall), "medium" (10–30 cm), and "large" (over 30 cm) gorgonian corals in Area BB throughout the study.

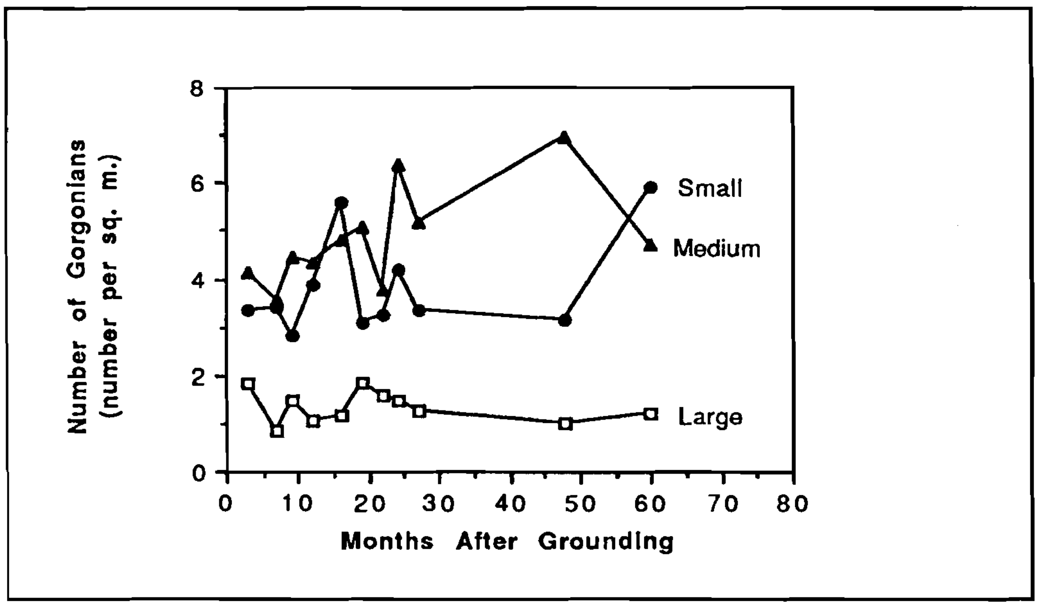

Figure 8. Density of "small" (0–10 cm tall), "medium" (10–30 cm), and "large" (over 30 cm) gorgonian corals in Area BB throughout the study.

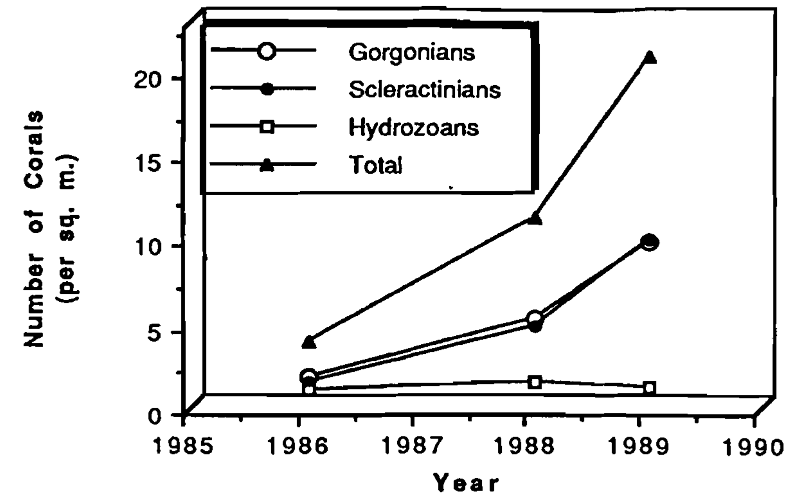

Figure 9. Gorgonian, scleractinian, hydrozoan, and total abundance of corals, as estimated by diver counting all corals in eighteen 1-m² quadrats in Area BB in November 1986, September 1988, and August 1989.

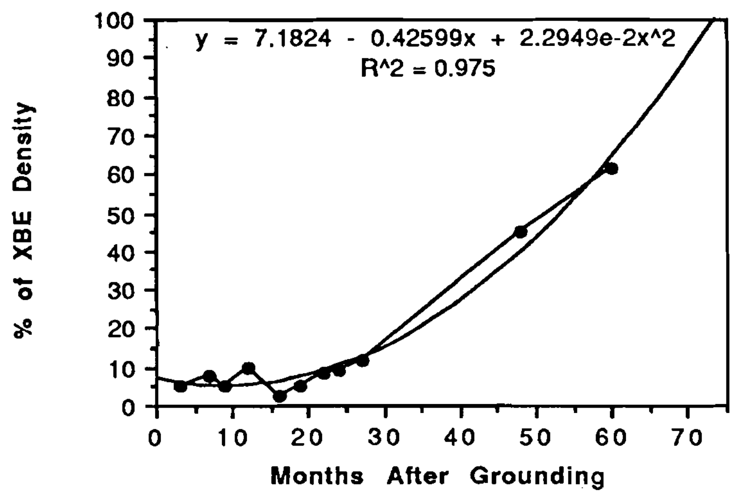

Figure 10. "Best fit" second order polynomial curve applied to coral population data in Area BB. Extrapolation predicts 100% recovery in terms of colony abundance at approximately 72 months following the grounding.