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FIFTY YEARS OF IMPACTS ON CORAL REEFS IN BERMUDA

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ABSTRACT

The high latitude coral reefs of Bermuda have been impacted by two major kinds of events since the early 1940's. The first was the dredging operation in Castle Harbour which led to the construction of Kindley airfield (now the Bermuda Air Terminal.) The associated sedimentation, turbidity and altered hydrology caused a mass mortality of corals, especially of the major reef-building genus *Diploria*. While there has been post-dredging recruitment of corals, *D. strigosa*, a species sensitive to sedimentation, has been particularly slow to recover and is less prevalent at this site than elsewhere in Bermuda. Ship groundings comprise the second class of event: since 1940, thirteen major ship groundings have occurred on the reefs which have destroyed an estimated 1% of the outer reefs. Studies of the recovery and recruitment of corals at a major grounding site indicate that these processes occur very slowly in Bermuda. It is estimated that 100 - 150 years would be required to restore coral coverage and species diversity, with species of *Diploria* being particularly slow to recover. Recent episodes of coral bleaching in Bermuda are considered to have had very little effect on coral populations and reefs.

INTRODUCTION

Located between latitudes 32° 15' and 32° 30' N, Bermuda has the highest latitude coral reefs in the Western hemisphere. The surface waters of the Sargasso Sea around Bermuda are warmed by Gulf Stream circulation, so that Bermuda is the northern limit of distribution for numerous species of Caribbean corals. During the winter, surface waters of the Sargasso Sea around the islands typically fall to 18-19°C and occasional cold fronts may drop inshore reef water temperatures as low as 14° (Morris et al., 1977). Hence, Bermuda's reef corals, which are Caribbean in origin, grow at slow rates relative to conspecifics elsewhere (Logan and Tomascik, 1991), and may be more sensitive to elevated temperatures (Coles et al., 1976; Cook et al., 1990). Since recruitment of corals is probably *only* through local reproduction (e.g., Smith, 1992), it would appear that Bermuda's corals, being at the limits of their range and likely temperature tolerances, would be slow to recover from mass mortality events.

As we shall discuss, the major events that have impacted Bermuda's corals and coral reefs over the past fifty years have been associated with human activities. Hurricanes have had relatively little effect: unlike Caribbean reefs that are dominated by relatively fragile, branching species of *Acropora* (unknown in Bermuda), Bermuda's reefs are dominated by massive boulder corals (Dodge et al., 1982; Logan, 1988) that are more resistant to storm wave energy. Rather, socio-political considerations underlie the potential for reef disturbance. The island's land mass of 20 square miles is home to a resident human population of 58,000, and attracts over half a million tourists annually. Situated at a crossroads in the North Atlantic, Bermuda's strategic position in the North Atlantic (Figure 1) has made it a focus of military operations. A major development was the construction of Kindley Airfield during World War II (now the site of the Bermuda Air Terminal). Dredging for the airfield and associated sedimentation and turbidity had immediate effects on the reefs of Castle Harbor, while the long-term impacts of this operation include the continued sedimentation effects and the use of Castle Harbor as a metal waste dumping site. Bermuda's location also makes the island's reefs vulnerable to ship groundings, with the potential for physical damage and pollution from spillage. At least one hundred vessels are known to have struck Bermuda's reefs since the time of colonization (1609).

In this paper we review the impacts of the Castle Harbor dredging operation, of the various ship groundings that have occurred since 1940, and the possible effects of recent elevated temperatures on coral bleaching in Bermuda. The effects of the Castle Harbor dredging are based largely on the study by Dodge and Vaisnys (1977) comparing corals in Castle Harbor with those from other Bermuda reefs. Coral losses associated with post-1940 ship groundings are compared with estimates of coral recolonization and growth on a recent ship grounding site (Smith, 1992). The effects of coral bleaching are based on the work of Cook et al. (1990), and subsequent surveys by Cook and Smith.

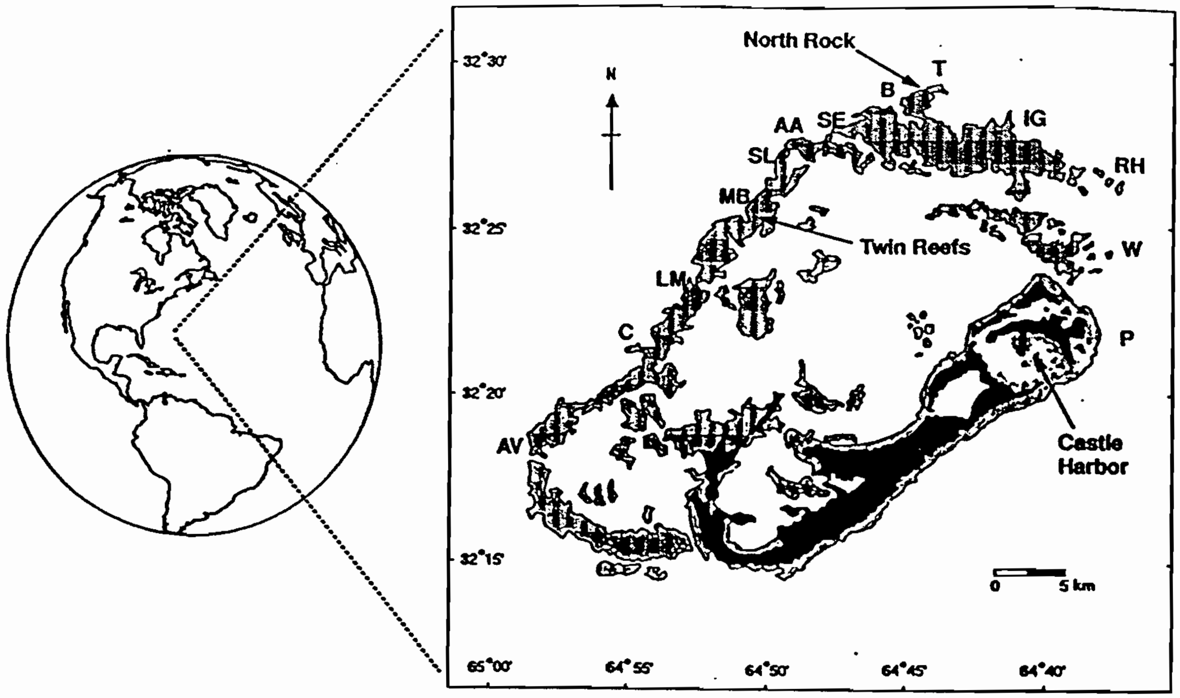

Figure 1. The location of Bermuda. The detailed map indicates the location of study sites (North Rock, Twin Reefs) and major ship groundings discussed in the text and Table 1. Black areas are land mass, while the stippled areas indicate reefal shoals (5m depth contour). (Modified from Logan, 1988)

MATERIALS AND METHODS

Castle Harbor Studies

Castle Harbor is a semi-enclosed basin, averaging 9 m in depth, and contains many reefs of 1-3m depth. These reefs range from shoal-like near shore and pinnacle or knoll-like in more open water (Figure 1). Kindley Airfield, a major geomorphologic feature surrounding the northern portion, was constructed by dredging Castle Harbor from 1941-1943 when 16-20 million cubic yards of fill were pumped to form the hard-packed airfield foundation. To assess the effects of sedimentation and turbidity on the corals of the Harbor, analyses were made between 1974 and 1976 of abundance, species distribution, growth patterns and age distribution of both living and dead coral assemblages from Castle Harbor reefs and from other undisturbed reefs external to the Harbor. Observations were made on living specimens of *Diploria* spp., and live specimens were collected from Castle Harbor as well as at a variety of stations representing reef types of the Bermuda platform.

Skeletal analysis. Dead coral specimens were collected from the harbor and sectioned with a diamond bit saw to obtain thin medial slabs. Slabs were X-radiographed and negatives printed to reveal annual density bands. Dates of density band formation were assigned by counting back from the known age of the living growth surface. Extension of each band was measured by calipers. Growth patterns were evaluated by plotting and comparing the yearly extension of colonies versus time, and colony age was estimated using the number of available growth bands and colony shape. Bioerosion and a pronounced lowering of extension rate at the death surface were factors in creating uncertainty about the uppermost bands, which represented the several years prior to death.

Ship Groundings

Occurrences of ship groundings. The major ship groundings on Bermuda's reefs over the past 53 years are listed in Table 1. Their location is given in Figure 1.

Estimation of reef damage from ship groundings. The size of the impact zone for each ship grounding was estimated by doubling the hull area (length * width). This is a conservative estimate because vessels that remain aground can be moved by storm waves causing additional reef damage, and larger vessels impacting at high speed are likely to have a larger impact area. Also, rubble and sediments created by the initial impact can be later mobilized by storm waves, and prop wash effects generated when the ship attempts to free itself can create significant additional impact, although this impact is difficult to estimate on an areal basis.

Estimation of recovery rates of ship grounding sites. Rates of recovery of reefs following ship groundings were estimated from the patterns of re-colonization and growth of juvenile corals following the grounding of the Mari Boeing in 1978 (Smith 1985, 1990, 1992). Coral surveys were conducted at two locations (ED and WD) at this site in 1986, 1989 and 1992. Twenty 0.25 m^2 quadrats were randomly deployed at each location in 1986 and 1989, and 10 0.25 m^2 quadrats were used in 1992. The maximum diameter or two most significant axes of each coral colony in a quadrat were measured with calipers and the two dimensional area of the colony was calculated.

Coral Bleaching

Transect surveys. Transect sites were set up at two northern rim reefs, North Rock and Twin Reefs (Figure 1). Colonies of scleractinian corals and *Millepora alcicornis* were surveyed using the point method (Dodge et al., 1982) along 20m transects. Five transects were made at each survey, with corals being scored along 10 cm points for bleaching condition ("normal", "pale", "blotched", "white", with the latter being live colonies with no evident coloration). For the purposes of this paper, all bleaching categories were combined. Random swim surveys were also taken at North Rock at other times to assess bleaching of *M. alcicornis*. Temperature records were made both on-site and from air / seawater records of the Oceanographic Command of the US Naval Air Station (NAS Bermuda).

RESULTS

Impacts on Castle Harbor Reefs

Species composition and abundance. Qualitative observations coupled with collection information revealed that in 1974 *Diploria strigosa* and *D. labyrinthiformis* were similar in abundance on reefs outside the Harbor, or that *D. strigosa* was predominant (q.v. Dodge et al., 1982). However, *D. labyrinthiformis* predominated in the Harbor, with virtually no *D. strigosa* older than fifteen years. Among the dead Castle Harbor corals, the two species were evenly split.. Living coral cover within the harbor was much less than outside, while the proportion of easily recognizable dead corals was much greater within the Harbor.

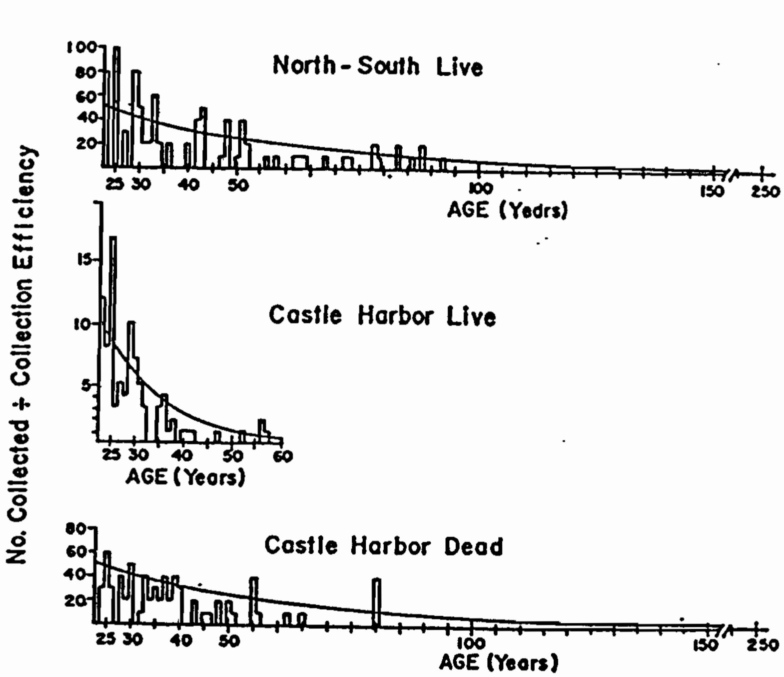

Figure 2. Age distributions of collected corals; "North and South live" refers to Bermuda corals collected from reefs outside of Castle Harbor. (From Dodge and Vaisnys, 1977)

Age distribution: The age structure of collected dead corals from Castle Harbor was similar to that of live corals outside the harbor (Figure 2, corrected for collection efficiency; Dodge and Vaisnys, 1977) while the living corals in the Harbor had a strikingly lower longevity and a higher rate of intrinsic increase than did the live corals from outside the harbor (Figure 2). Particularly evident is the absence of larger living corals from the harbor.

Growth Pattern Analysis: Specimens of contemporary Bermuda *Diploria* spp. had similar patterns of extension growth from year to year. For many of the dead corals of Castle Harbor the growth patterns also had common features. Particularly obvious was a decline in extension rate prior to death, suggesting a stress period preceding mortality.

Recovery from Ship Groundings

Extent of ship groundings in Bermuda since 1940. Table 1 summarizes the estimated impact zone for the major ship groundings since 1940. By our conservative estimates, 73 hectares of reef, or 1% of the total outer reef area, have been damaged by these vessels and attendant salvage operations. Most of these vessels were stranded on shallow reefs (< 10m) but two oil tankers, *Tifoso* and *Aquila Azteca*, grounded on the deeper outer terrace at 18-20 m. Site visits to recent groundings (*Mari Boeing*, *Tifoso* and

Sealuck; Smith 1985 and unpubl.) confirmed that coral was devastated in the areas under the hulls of the ships, leaving virtually n viable fragments, and that extensive peripheral areas adjacent to the grounded vessels were also severely disturbed.

After 14 years, only 3-4% of the reef surface is covered by live coral at the *Mari Boeing* site (Figure 3). This is in contra to the more typical values of 20-40% seen on undisturbed reefs such as North Rock (Dodge et al., 1982). The current rate of coral re-colonization and growth is about 25 cm^2 m^{-2} yr^{-1}, and is very similar to estimates of re-growth at the site from 1980-84 (Smith 1985). Given coral coverage on undisturbed Bermuda reefs of 20-40% (Dodge et al., 1982), it would take 80-160 years before cor coverage would be similar to that prior to the accident.

Table 1. Major ship groundings on Bermuda's reefs 1940-1993. Specific information about some groundings, such as movement of a ship on a reef or later sinking at a site different from the site of grounding was used to increase estimates of impact, usually by a factor of 2. 4-6 additional groundings occurred during W.W.II but were never reported for security reasons (T. Tucker, pers. comm.). Groundings by smaller yachts were not tabulated.

Vessel	Date	Site[1]	Length of ship (m)	Estimated area of impact (m^2)
Pelinaion	16 Jan 1940	St. David's Head (P)	117	3500
Constellation	July 43	Western Blue Cut (C)	60	1200
Whychwood	9 Nov 1955	Mill's Breaker (W)	95	9000
Ivan Gorthon	25 Nov 1958	NE Breaker (IG)	~75	500
Safina Ejamoorijat	25 Mar 1961	Leghorn Rock (SE)	135	100,000
Baltika	31 August 1973	W. of North Rock (B)	~136	7000
Rio Haina	30 Dec 1976	Kitchen Shoals (RH)	~60	2500
La Maria	29 Sep 1977	E. Blue Cut (LM)	153	9000
Mari Boeing	27 Dec 1978	Hog Breaker (MB)	160	400,000
Arcadian Victory	24 Feb 1980	Chubb Heads (AV)	63	1200
Tifoso	20 Jan 1983	E. of North Rock (T)	225	100,000
Sealuck	15 Sep 1984	W. of North Rock (SL)	~181	4000
Aquila Azteca	10 Jan 1984	W. of North Rock (AA)	302	90,000
Estimated area of damaged reef (total)				73 hectares
Total of outer reef:				~101,000 hectares
Estimated amount of reef area lost (%):				~1%

[1] Number in parentheses refers to location on Figure 1.

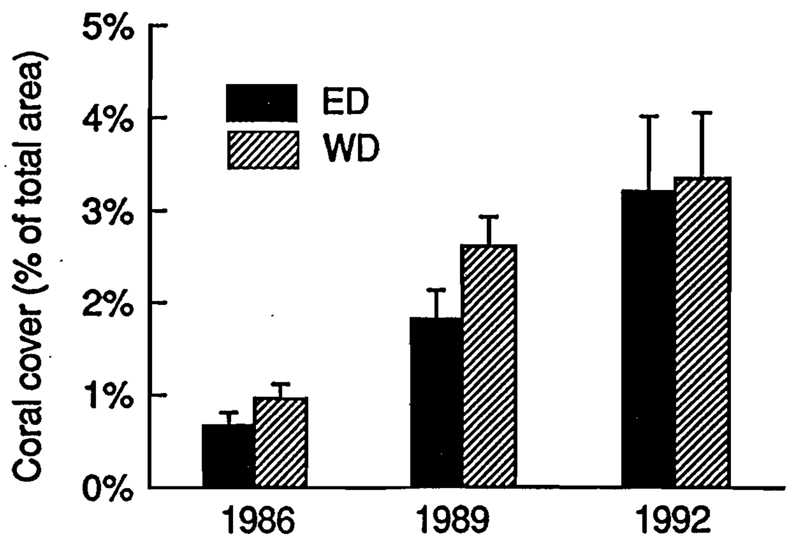

Figure 3. Mean percentage coral cover (± SEM) at two study locations on the *Mari Boeing* site in 1986, 1989 and 1992, showing recruitment and growth since the 1977 grounding incident.

The dominant recruiting coral is *Porites astreoides* and the largest colony observed to date is about 100 cm^2 in size. Other common coral recruits were *Favia fragum* and *Siderastrea radians*. The dominant corals on Bermuda's reefs, *Diploria strigosa* and *D. labyrinthiformis*, have recruited very slowly to the grounding site and the largest observed colonies of these species are only about 20 cm^2 in size (Smith 1990, 1992; unpubl. data.)

Coral Bleaching

Bermuda has had two summers with record warm temperatures since 1986, according to NAS Bermuda records. 1988 had the longest period of prolonged warmth, both in air temperatures (NAS Bermuda) and sea surface temperatures (Cook et al., 1990). 1991 was the second warmest summer in NAS records. Reef water temperatures exceeded 29°C during much of these periods. During both of these periods (August through September 1988, July - August in 1991) bleached corals were evident on Bermuda's reefs, with *Millepora alcicornis* being the species most affected (Figure 4). Although the transect data of Figure 4 were taken from different sites in 1988 and 1991, random swim surveys during this period at the North Rock showed less but still significant bleaching (24 July 91: 22.6% of 53 colonies bleached, T = 27.8°; 6 August 91, 47.3% of 87 colonies bleached, T = 29.4°; 21 October 1991, 13.6% of 83 colonies bleached, T = 26.7°).

Neither the 1988 nor 1991 events produced known coral mortality at our sites, and recovery was evident within 3-4 months (Figure 4). The prevalent white patches of *M. alcicornis* during these periods were evident even to casual observers, but not during cooler summers or during any fall through winter periods, when surveys revealed little if any bleaching.

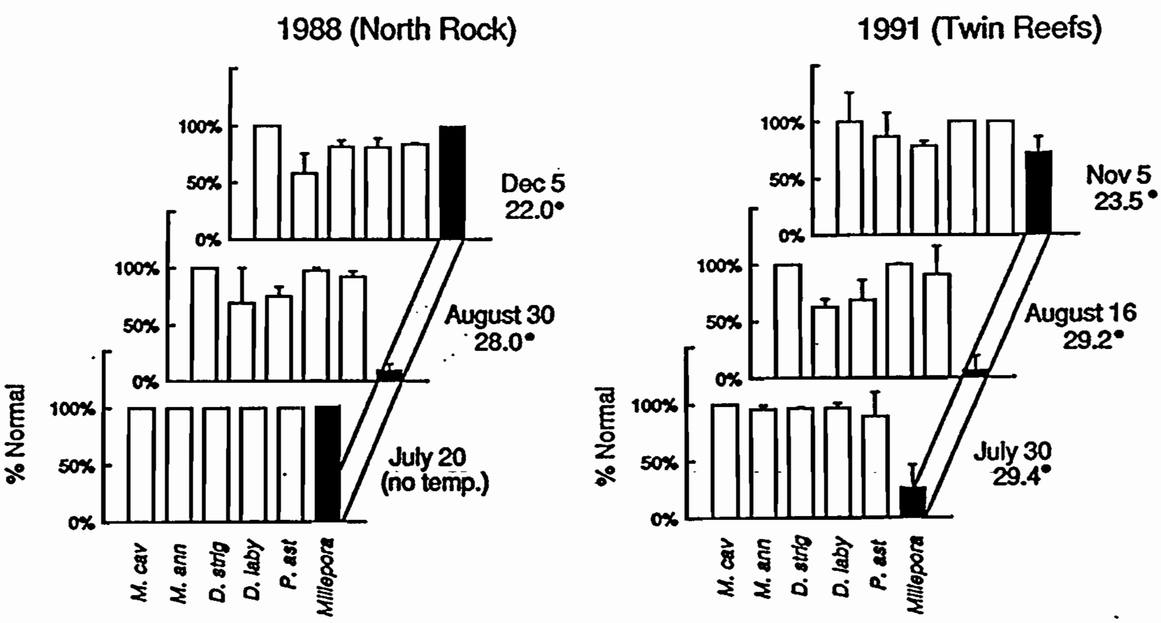

Figure 4. Coral bleaching by species at North Rock and Twin Reefs sites, 1988 and 1991. 1988 data from Cook et al. 1990. Solid bars represent data for *Millepora alcicornis;* scleractinian species are indicated by open bars. Temperatures at 7-9m depth are indicated. Vertical bars are ± SEM.

DISCUSSION

Impact of Dredging on Castle Harbor Reefs

The striking differences in the age structures of living corals inside and outside Castle Harbor, and between living and dead corals in the harbor, still exist today (cf. Logan, 1988, p. 54). The greater longevity of corals from reefs other than Castle Harbor and the higher r (intrinsic rate of increase) of the Castle Harbor population (Dodge and Vaisnys, 1977) suggested a recovering coral population in the harbor. The low maximum age of corals in the harbor suggested a past event had occurred which had eliminated most of the harbor's older corals; the reduced coral coverage and abundance in the harbor supported this conclusion. In addition, there has been a change in the species composition of Castle Harbor corals. Prior to the dredging activities, *D. strigosa* and *D labyrinthiformis* were equally abundant; in the 1974 surveys, *Diploria labyrinthiformis* was the predominant species. On other reefs in Bermuda, the two species are of equal abundance, or *D. strigosa* predominates (Dryer and Logan, 1978; Dodge et al. 1982;

data of Cook et al., 1990). *D. labyrinthiformis* is better adapted for sediment rejection than *D. strigosa* (Hubbard and Pocock, 1972).

Thus, dredging for airfield construction in 1941-43 is concluded to have caused a major disturbance in Castle Harbor. The actual dredging activities increased sedimentation and turbidity, both of which can have detrimental effects on corals (Rogers, 1990). These effects together with subsequent changes in circulation were instrumental in causing a catastrophic mass mortality of corals. Analysis of growth patterns supports this conclusion. Dead corals showed a similar pattern of growth but with a marked decline prior to death. This is consistent with a population which suffered mass mortality

Today there is a relatively sparse population of various hermatypic corals on the Castle Harbor reefs,. Species composition and abundance indicate that the reef ecology has not returned to pre-dredging conditions, even after 50 years from the initial disturbance. Yet these corals still cope with sedimentation problems. The airport site is now the location of the metal dump for the island, although it is not clear that Castle Harbor corals are impacted by metal pollution (Jickells and Knap 1984). The effects of a proposed toxic ash disposal plan for the harbor and its reefs have yet to be determined.

Ship Groundings

Damage and recovery of reefs after ship groundings A significant area of Bermuda's outer reefs has been severely damaged by ship groundings in the past 53 years. The physical effect of these groundings has been the complete elimination of all living coral over varying spatial scales, from a few hundred m^2 to hectares. The re-growth of coral at the Mari Boeing grounding site indicates that coral recovery rates are very low on Bermuda's outer reefs, on the order of at least a century for the re-establishment of typical coral coverage. Thus the relatively high frequency of groundings on Bermuda's reef over the past 50 years has produced a cumulative effect on coral populations due to this very slow recovery rate.

The semi-quantitative estimate for recovery does not take into account the species composition and size frequency distribution of corals that constitute normal reef assemblages. This consideration is important because of the great contribution large colonies make to the reproductive output of the entire population (Hughes et al., 1992) The two dominant reef-building corals in Bermuda (*D. strigosa* and *D. labyrinthiformis*) appear to be very poor recruiters, presumably because of their broadcast mode of spawning (Smith 1992). These two species also have slow growth rates in Bermuda, with <0.5 cm radial growth per year (Dodge, 1978). Thus, it may take much longer for these corals to repopulate damaged reefs and reach sufficient size to initiate sexual reproduction. It is noteworthy that *D. strigosa* has been also slow to recover in Castle Harbor, emphasizing the sensitivity of this major reef-building species to mass mortality events in Bermuda.

Associated effects of ship grounding. The loss of reef structure and topography that accompanies a ship grounding appears to have a significant effect on reef fish activity. Smith (1988, 1990) monitored the grazing activity of fishes at the Mari Boeing site and found that grazing rates were reduced. He attributed these observations to the lack of refuge from predators and the size of the area that had been disturbed. The implication is that the reefs damaged by ship groundings have reduced secondary productivity and this situation would remain in effect for decades until sufficient coral re-growth would take place to provide fishes with sufficient shelter from predation.

Fortunately there has been little impact of oil spills from any of these grounding incidents. A summary of the oiling incident associated with the grounding of *Tifoso* and the Bermuda government's contingency plan are reviewed by Knap et al. (1985).

Coral Bleaching

In comparison to other areas that have been affected by coral bleaching. the few events associated with warm temperatures in Bermuda have been relatively minor, with no long-lasting effects; there are no confirmed instances of coral mortality. *Millepora alcicornis* appears to be the most sensitive species in Bermuda, and we now believe that is species is an indicator for warm-temperature bleaching events in Bermuda. Other species of *Millepora* are also sensitive to elevated temperatures (*e.g.* Glynn and de Weert, 1991), so that members of the genus may be appropriate indicator species on other reefs.

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CONCLUSION

Both the dredging of Castle Harbor in the early 1940's and ship groundings over the past 53 years have deleteriously affected Bermuda's reefs. Sedimentation, turbidity and altered hydrology resulting from the dredging operation produced mass mortality of corals, and the major reef-building species in Bermuda (*Diploria strigosa*) has been very slow to recover. On ship grounding sites coral recovery is slow because of poor recruitment and slow growth by *Diploria* spp.. Reef fish populations are reduced on grounding sites and may remain depressed until sufficient coral growth has occurred. Coral bleaching has had little impact on Bermuda reefs.

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