Coral Reefs (2002) 21:49–56
DOI 10.1007/s00338-001-0198-1

REPORT

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# Evidence from aerial photography of structural loss of coral reefs at Barbados, West Indies

Received: 9 February 2001 / Accepted: 25 April 2001 / Published online: 2 February 2002


**Abstract** In response to concerns about widespread degradation of coral reefs at Barbados, West Indies, over the past two decades, maps and planimetric areas of 20 fringing coral reefs were estimated from enlargements of aerial photographs of the island, using geographic information system analysis. There were statistically significant reductions in reef areas over a 40-year period from 1950 to 1991. Areal losses exceeding measurement and boundary interpretation errors of 10% were detected on eight of the 20 reefs. Ground validation carried out by divers on six of the reefs confirmed physical losses of reef structures and accumulation of rubble and sand substrata at sites where substantial planimetric area loss was detected on aerial photographs. Structural losses occurred along the "spur and groove" system of the reef-seaward edge, within deep channels or breaches in the reef front, and along the flanks or ends of reefs. The location and nature of the observed losses suggest that storm damage and seasonal alterations in beach morphology are the two most important factors contributing to geomorphological structural loss of the reefs.

**Keywords** Coral reefs · Barbados · Aerial photography · Planimetric area · Structural loss

## Introduction

Amongst coral reef biologists, there is a strong perception of worldwide degradation and decline of reefs and related ecosystems over the past several decades (Brown 1987; Grigg and Dollar 1990; Williams and Bunkley-Williams 1990; Smith and Buddemeier 1992; Wilkinson 1993; Buddemeier and Smith 1999). The cause of this decline is generally attributed to environmental stress related to a combination of natural and human environmental disturbances (Buddemeier and Smith 1999; Done 1999). Recognition of the importance of worldwide devastation and concern for the future of coral reef ecosystems have been expressed in numerous reports at international symposia (Wilkinson 1999) and in the establishment of the International Coral Reef Initiative (ICRI) to promote the conservation and management of coral reefs (Dight and Scherl 1997).

Symptoms of reef decline may include skeleton breakage and loss of live coral cover, changes in community composition and loss of species diversity, widespread coral bleaching, reduction in reproductive output and recruitment, disease, and death (Connell 1997; Done 1999; Wilkinson 1999). Where these indicators consist of superficial (surface) changes in community composition, there would appear to be potential for recovery, should circumstances improve. Indeed, coral assemblages on reefs are subject to short- and long-term variation, destruction, and recovery (Connell 1997; Connell et al. 1997). On some reefs, however, more severe structural, framework damage has occurred with less potential for recovery (Stoddart 1963, 1974; Hubbard et al. 1994; Hughes 1994; Tomascik et al. 1994; Done 1999).

The decline of the once-flourishing reef system at Barbados has been reported by Bell and Tomascik (1994) and Scoffin (1994). The cause of the deterioration was attributed to eutrophication resulting from urbanization, poor agricultural practices, and sewage discharge (Tomascik and Sander 1985, 1987), to storm damage (Mah and Stearn 1986), and grazing by herbivorous sea-urchins (Wittenberg and Hunte 1992; Allard 1993). Amongst the adverse effects have been declines in the abundance and diversity of corals and impairment of growth, reproduction, recruitment, and other life-history traits (Tomascik and Sander 1985, 1987).

Although these accounts do not report severe structural damage, early anecdotal accounts of shallow water reefs around Barbados (Nutting 1919; Butsch 1939)

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suggest extensive loss of whole fringing reefs before 1950 but lack empirical evidence. Destruction of fringing reefs bordering the southwest corner of the island at Bridgetown (Fig. 1) between 1950 and 1972 was reported by Lewsey (1978).

The purpose of the following investigation was to map and determine the extent of structural changes that have taken place over a 40-year period between 1950 and 1990 on fringing reefs at Barbados, based on evidence from aerial photographs of the island. Thus, the reefs are described according to their geomorphology rather than explicit ecological properties (Kuchler et al. 1986; Green et al. 1996) but can be reasonably equated with reef habitat. Because of the common existence and variable quality of aerial photographs, special attention is paid to estimating the accuracy of measurement for guidance of other investigators.

## Methods

Present-day fringing coral reefs on the west coast of Barbados extend over a distance of about 18 km between Paradise Beach in the south and Smitons Bay in the north (Fig. 1). They extend for 100–150 m from the shore to depths of 5–6 m. Descriptions of the reefs have been reported by Lewis (1960), Stearn et al. (1977), and Lewis and Oxenford (1996). They are similar in general features to reefs described elsewhere in the Caribbean (Wells 1988) and are characterized by marked coral zonation consisting of a shoreward "back reef", a middle "reef crest", and a seaward "spur and groove" system.

### Area determination

Charts and planimetric areas of the reefs were estimated from aerial photographs of Barbados, using geographic information system (GIS) analysis. Aerial photographs of the west coast of the island were obtained from the archives of the Government of Barbados, Department of Lands and Surveys, Bridgetown, and from the National Air Photo Library of Canada, Ottawa. Black-and-white aerial photographs, at a scale of 1:12,000 were taken in December 1950 and a color aerial photographic survey at a scale of 1:10,000 was completed in March 1991.

Reef areas on aerial photographs were first rephotographed and enlarged for detailed examination. Image distortion on aerial photographs as reported by Green et al. (1996) and Mumby et al. (1995) was not detected nor was there any apparent decrease in resolution of the copied images from the original photographs. Scales of enlarged photographs were corrected with reference to 1:10,000 topographic maps (First Edition) compiled by the Directorate of Colonial Surveys, London, England. Reef areas on corrected photos were scanned at 600 dpi resolution using a Microtek Scanmaker 5 in a Macintosh G3 system, and Adobe Photoshop 5 with Scanwizard PPC 3.1.2 for imaging. Images were enhanced individually so as to maximize the clarity of reef boundary outlines and checked against the original photographs. The presence of sandy bottom seaward of the "spur and groove" zone allowed easy recognition of the boundary between the two zones. Where limits of the reefs were ambiguous, interpretation was improved by reference to the original aerial photographs using a binocular microscope (Wild M5, 6-50X objective, 10X eyepiece). Examples of photographic enlargements of reefs at Paynes Bay and Sandy Lane are shown in Figs. 2 and 3.

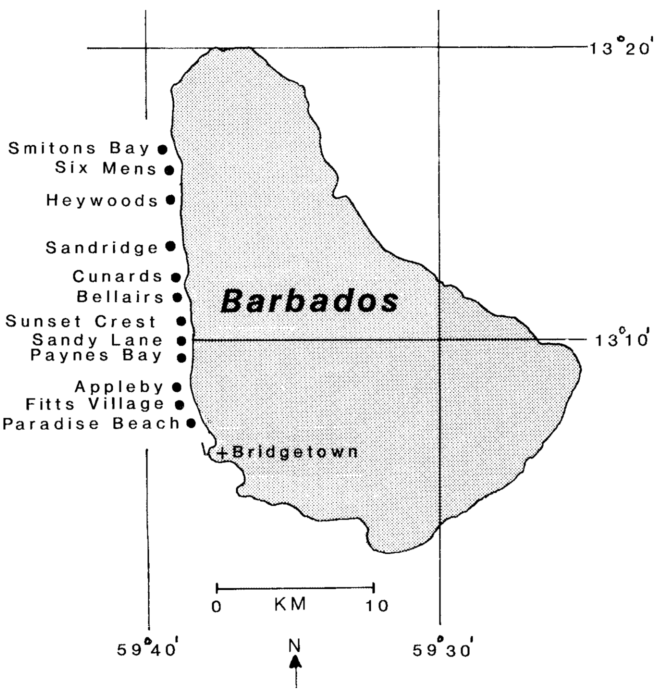


**Fig. 1.** Map of Barbados showing locations of fringing reefs

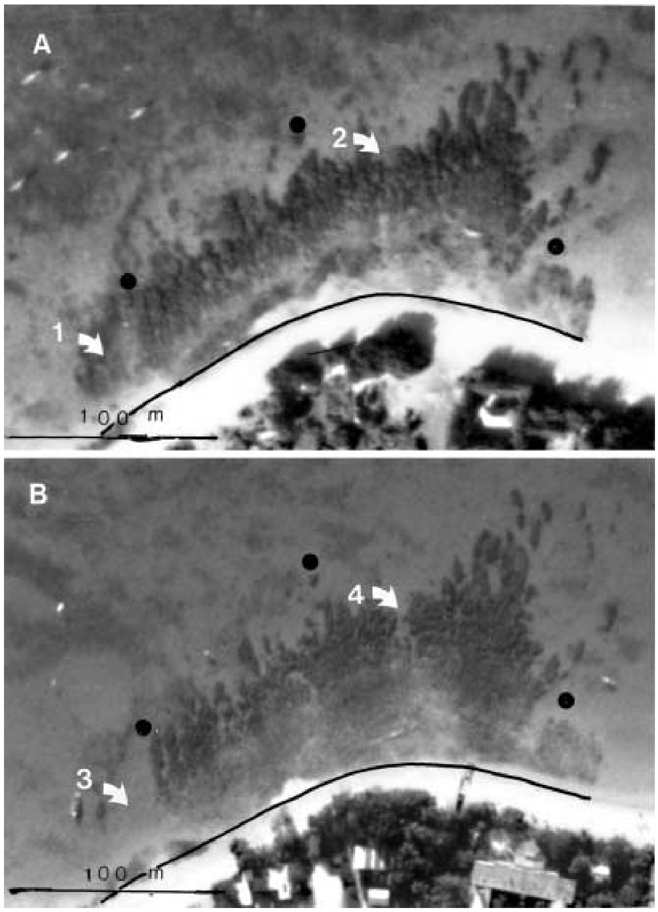


**Fig. 2.** Enlargements of Paynes Bay 1 reef from **A** 1950 and **B** 1991 aerial photographs. *Solid circles* are visual reference coordinate points. *1* South reef flank; *2* notch in spur and groove zone; *3* sand- and rubble-covered south reef flank; *4* sand- and rubble-filled breach in spur and groove zone. *Solid line* is 1950 reference shoreline defining inner edge of reef

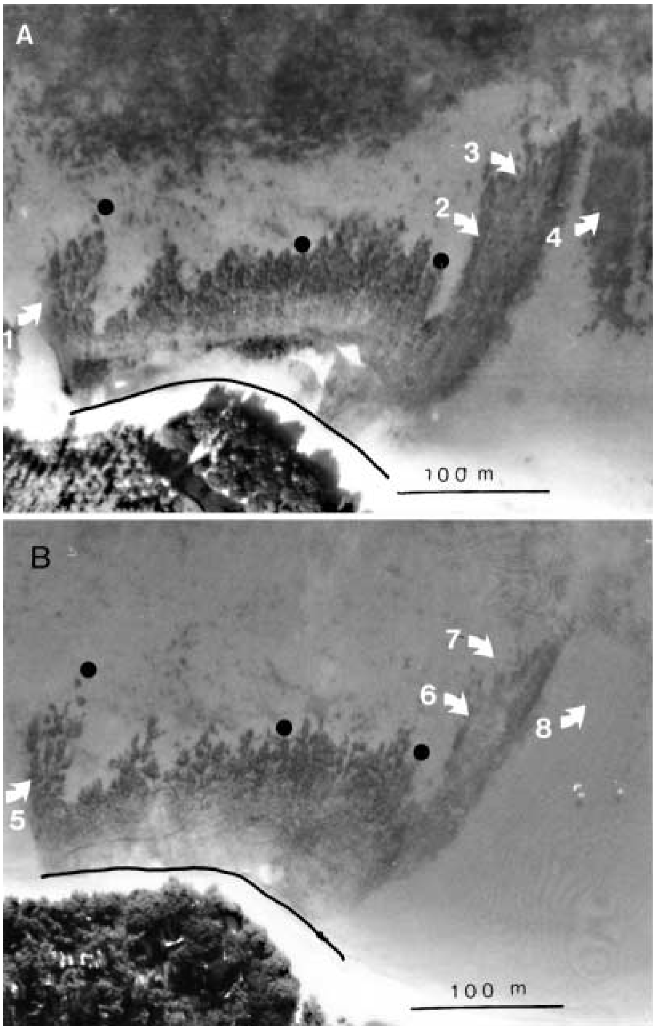


**Fig. 3.** Enlargements of Sandy Lane 2 reef from **A** 1950 and **B** 1991 aerial photographs. *Solid circles* are visual reference coordinate points. *1* South reef flank; *2* margin of reef arm; *3* seaward edge of reef arm; *4* adjacent reef; *5* reduced south reef flank; *6* reduced margin of reef arm; *7* sand- and rubble-covered seaward margin of reef arm; *8* sand-and rubble-covered area of adjacent reef. *Solid line* is 1950 reference shoreline defining inner edge of reef

Areas of reef enlargements were determined manually (mean of a minimum of three replicates) with a compensating polar planimeter (Keuffel and Esser) from tracings of the perimeter of each reef. Hand-drawn outlines of the reefs were made on tracing overlays superimposed on the aerial photograph enlargements. Each outline formed a continuous line that excluded separated or isolated portions of the reefs. A minimum of three prominent features clearly visible on both 1950 and 1991 photographs were located and marked as reference coordinates on scanned copies in order to facilitate comparisons.

Because beach shoreline widths vary seasonally (Bird et al. 1979) and may temporarily conceal parts of the back reef, a reference baseline, defining the inner edge of each reef, was plotted on the 1950 photo enlargements. The 1991 reef enlargements were normalized to the 1950 baseline reference, using an overlay technique which matched reference points and thus equalized the spatial scales between the reef pairs.

In order to estimate accuracy of measurement techniques and reduce bias in comparison of 1950 and 1990 reef areas due to subjective determination of reef boundaries (Green et al. 1996), enlargements (without identifying labels) were randomly sorted before tracing boundaries and hand digitizing. To estimate the variation in determinations of reef boundaries, 35 replicate measurements were performed on randomly selected reefs and on 20 additional random reef measurements by an independent observer. The random selections included samples of all 20 reefs.

### Field verification

The importance of field verification or "ground truthing" of remotely sensed data has been emphasized by a number of authors (Thramrongnawasawat and Catt 1994; Thramrongnawasawat and Hopley 1995; Mumby et al. 1998). Where the data required are finely detailed estimates of benthic cover, then dense quadrat sampling is necessary. However, semi-quantitative methods such as belt transects or manta tows have been used successfully for mapping large-scale reef geomorphology (Mumby et al. 1997). Thus, visual inspection along underwater transects referenced to ground control points is appropriate for whole reef mapping (Green et al. 1996).

Ideally, the collection of ground data should be synchronized with the time of collection of remotely sensed data where conditions on the ground are likely to change over the short term (Mumby et al. 1997). For example, monitoring habitat changes in coral cover or species composition would normally require synchronous verification (King 1995). Because the spatial and temporal scales of structural changes on the reefs measured here are much larger than changes in surface coral cover, a delay in ground verification should less seriously affect its accuracy. Delayed ground verification will still confirm area loss from the 1950 limits. Where further loss of reef has occurred since 1991, delayed verification will be equal to or exceed the 1991 photo estimates, unless recovery has occurred.

Eight locations on six reefs where substantial areal loss between 1950 and 1991 was detected on the aerial photographs were selected for in-situ ground validation in January 1996. Enlarged images of aerial photographs of each site were copied onto underwater slates in the form of line drawings and defined areas of loss were marked for validation. A pair of divers first located and marked reference features from the reef onto the slates. A system of belt transects to be followed by the divers was established within the area marked for validation. Divers first verified the condition of specific surface features marked as areas of loss and then reef boundaries were superimposed on the drawings on the underwater slates. Explanations of reef features employed during ground validation are contained in Table 1.

## Results

Planimetric areas of 20 fringing reefs on the west coast of Barbados, estimated from aerial photographs, are shown in Table 2. There was a decrease in areas between 1950 and 1991 on all reefs except for Sunset Crest 2. A paired sample t-test showed that the differences (losses) were significant ($t = 4.033$, $p = 0.001$). There was a combined area loss of 8.4 ha from all reefs and a mean loss of 0.42 ha ($SE = 0.109$) or 11.05%. The minimum loss of area (0.03 ha or 1.9%) occurred on Bellairs 2 reef and the maximum loss (2.75 ha or 23.2%) occurred on Heywoods reef. There was no apparent north/south trend in percent area loss nor was percent loss correlated with size of reefs (Bartlett chi-square statistic = 0.894, $df = 1$, $p = 0.349$). There was a mean difference in planimetric areas of 8.6% between replicate paired samples ($n = 35$, $SE = 1.38$) and a mean difference of 7.9% between replicate paired samples of a second observer

**Table 1.** Explanation of reef features used in field verification

| Feature | Explanation |
|---|---|
| Spur and groove zone | This is the configuration of the seaward front of fringing reefs, alternating ridges and irregular valleys oriented perpendicular to the shore. There is a gradual slope of the reef spur surface from 1–3 m depth at the inner edge to 5–6 m depth at the outer end |
| Spur tips | The seaward ends of the spurs are low ridges 1–2 m in height, covered with the corals *Porites porites* and *Madracis mirabilis* and flanked with *Montastrea annularis*, *Siderastrea siderea*, and *Diploria* spp. |
| Outliers | Clumps of corals lying beyond the spur tips. They consist of colonies of the corals *Montastrea* spp., *Siderastrea siderea*, and *Diploria* spp. They may be aligned with the spurs or scattered at some distance from the spur tips |
| Breaches | Wide breaks in the spur and groove zone which extend inwards through the reef crest and back reef zones to the shore |
| Flanks | The extreme ends of individual reefs, narrow in width and terminating at a beach in shallow water |

($n=20$, SE = 1.32). Thus the variation in the determination of the reef boundaries was just less than 10% in 55 cases. Eight of the reefs lost more than 10% of their planimetric areas.

The mean difference in replicate paired samples between 1950 and 1991 was not significant ($t=1.28$, $p=0.209$), indicating that the variation in determination of boundaries was not due to the age of the photographs. The mean differences in replicate paired samples between the two sets of digitizers was also not significant ($t=1.39$, $p=0.233$), suggesting that these differences were random and not systematic. There was a small variation in mechanical measurement of perimeter outlines of 2–3%.

Details of reef losses as seen from aerial photographs and ground verification observations are shown in Table 3. Field observations supported substantial losses of reef structure at sites selected at Paradise Beach, Paynes Bay, Sandy Lane, Cunards, and Six Mens (Fig. 1).

**Table 2.** Planimetric areas (ha) of fringing reefs along the west coast of Barbados determined from 1950 and 1991 aerial photographs

| Reef | 1950 area | 1991 area | Area loss | Percent loss |
|---|---|---|---|---|
| Paradise Beach 1 | 1.98 | 1.67 | 0.31 | 15.6 |
| Paradise Beach 2 | 2.97 | 2.76 | 0.21 | 7.1 |
| Fitts Village 1 | 2.94 | 2.76 | 0.18 | 6.1 |
| Fitts Village 2 | 2.72 | 2.51 | 0.21 | 7.7 |
| Appelby | 3.60 | 3.50 | 0.10 | 2.7 |
| Paynes Bay 1 | 1.92 | 1.47 | 0.45 | 23.4 |
| Paynes Bay 2 | 2.15 | 1.69 | 0.46 | 21.4 |
| Sandy Lane 1 | 3.80 | 3.74 | 0.06 | 1.6 |
| Sandy Lane 2 | 3.67 | 2.99 | 0.68 | 18.5 |
| Sandy Lane 3 | 5.22 | 4.72 | 0.50 | 9.6 |
| Sunset Crest 1 | 2.36 | 2.22 | 0.14 | 5.9 |
| Sunset Crest 2 | 1.09 | 1.10 | +0.01 | +0.9 |
| Bellairs 1 | 3.69 | 3.47 | 0.22 | 5.9 |
| Bellairs 2 | 1.61 | 1.58 | 0.03 | 1.9 |
| Cunards 1 | 5.84 | 5.42 | 0.42 | 7.2 |
| Cunards 2 | 2.20 | 1.90 | 0.30 | 13.6 |
| Sandridge | 6.10 | 5.50 | 0.60 | 9.8 |
| Heywoods | 9.25 | 7.10 | 2.15 | 23.2 |
| Six Mens | 3.12 | 2.36 | 0.76 | 24.3 |
| Smitons Bay | 3.84 | 3.21 | 0.63 | 16.4 |

## Discussion

Prior to the launch of the first Landsat satellite in 1972 remote sensing of land surfaces was based on aerial photography (Green et al. 1996). Although improved techniques of remote sensing are currently in use for mapping shallow water coastal areas, the use of low level aerial photography combined with field verification still has much to recommend it (Hopley 1978; Sheppard et al. 1995; Green et al. 1996). Where the requirement is for detection of coral reefs, photographs may produce consistently better results than digital imagery (Kuchler 1986).

The availability of aerial photographs of Barbados, taken in 1950 and 1991 and archived by the Government of Barbados, provided the opportunity to examine changes that have occurred on fringing reefs over a 40-year period. From visual interpretation and GIS analysis of these photographs, it has been possible to map and estimate the planimetric areas of 20 reefs on the west coast of Barbados.

It should be noted, however, that there are limitations to the objectivity of interpretations of aerial photographs and that an assessment of accuracy of image classification for mapping is essential (Mumby et al. 1995; Green et al. 1996). Assessment of accuracy has been achieved by replication of image measurements and determination of standard errors. Thus the variation in determination of reef boundaries of 8.6% for paired replicate samples and of 7.9% for replicate paired samples of a second observer indicate an accuracy limit of nearly 10%. Eight of the fringing reefs had losses of greater than 10% and thus can be regarded as having lost planimetric area within this confidence limit. Although losses of less than 10% were found on 12 reefs, the consistent pattern of area loss found on all reefs but one supports the suggestion that there have been structural losses in addition to the superficial deterioration reported by Bell and Tomascik (1994) and Scoffin (1994).

Field validation by diver/observers of areal loss at eight specific sites confirmed the structural loss of coral framework estimated from aerial photographs. Three types of structural loss could be distinguished among the 20 reefs investigated. A major site of the damage

**Table 3.** Reef losses as seen from aerial photographs and ground verification observations

| Reefs | Reef loss from aerial photographs | Ground verification observations |
|---|---|---|
| Paradise Beach 1 | A comparison of the 1950 and 1991 photographs (Fig. 2) indicates a substantial loss of planimetric area in the southern sector of the reef. The 1991 traced outline shows a broad breach in the reef front near the southern flank (Fig. 4a) corresponding to an irregular indentation in the boundary of the 1950 outline | The broad breach cutting through the southern sector of the reef front reached almost to the shore and along most of its length was filled with coarse rubble and sand (Fig. 4a). The seaward end had a sandy bottom with scattered rubble. Only sparse coral cover (*Porites* sp.) was observed on the reef crest, adjacent to the breach |
| Paynes Bay 1 | The difference between outlines of 1950 and 1991 photographs (Fig. 4b) indicates loss of a large section of the southern flank of the reef. Recession of the 1950 perimeter appears along the whole southern end from the reef front to the shore | A large section of the southern flank of the reef from the reef front to the shore was covered with sand and rubble between the 1950 and 1991 perimeters. A prominent spur shown on the 1950 reef outline (Fig. 4b) was reduced to rubble except for a single remaining coral-covered outlier |
| Paynes Bay 2 | Aerial photographs indicated two major sites of loss on this reef. The traced outlines (Fig. 5b) show loss of planimetric area along the northern flank and within a broad breach in the central region | The northern flank between the lines of 1950 and 1991 perimeters (Fig. 5b) was composed of coarse rubble along the inner edge and covered with fine rubble and sand along the seaward edge. A section of the reef of low relief (2–3 m) remained within the former 1950 perimeter and consisted of coarse rubble with scattered live corals (*Porites* spp., *Agaricia* sp., *Millepora* sp.). In the central region of the reef there was a wide breach that exceeded the limits of the former 1950 channel boundary (Fig. 5b), extended to the shore, and was filled with rubble and sand. Around the mouth of the breach, several outliers which were prominent in the 1950 aerial photographs were reduced and covered with rubble and sand |
| Sandy Lane 2 | A prominent extended limb at the northern end of this reef is shown in the aerial photographs in Fig. 3. Comparison of the 1950 and 1991 outlines (Fig. 6a) shows shrinkage around the margin of the limb as well as a retreat of part of the central, adjacent reef front perimeter | The limb was observed to be a feature of low structural relief (1–2 m high) composed of branch ing and massive corals, similar in composition to the seaward sloping ridges of the reef spurs. The width of the limb has been reduced from the 1950 perimeter and was edged with rubble and sand. The central area of the limb consisted of mixed rubble and sand bottom with sparse patches of live coral. The adjacent area of the reef south of the limb consisted of a mixture of sand and coarse rubble between the 1950 and 1991 perimeters (Fig. 6a) |
| Cunards 2 | The traced outlines of aerial photographs (Fig. 5a) show are treat and loss of the seaward ends of spurs along much of the 1950 reef front | Disruption of the spur and groove system between the 1950 and 1991 perimeters was confirmed by field observations and the spur tips were generally eroded and partly covered with rubble and sand (Fig. 5a). Several new grooves cutting through the perimeter of the 1950 outline were identified |
| Six Mens | Major losses in planimetric area in the southern sector are shown in the traced outlines (Fig. 6b) of aerial photographs of this reef. There was a recession of the 1950 perimeter along most of the reef front and only isolated outliers remain in the region of the southern seaward flank of the 1991 perimeter | Field observations revealed a reef of low relief in shallow water (3–4 m along the reef front). Exam ination confirmed the recession of the former 1950 perimeter and the remains of numerous outliers (shown by dotted lines) seaward of the 1991 perimeter (Fig. 6b). These outliers consist of clumps of live coral (*Millepora* sp., *Porites* spp., *Montastrea* sp.) and of rubble partially smothered by sand |

and loss of reef structure was found along the seaward edge of the reefs, in the "spur and groove" zone (see Table 1). The low ridges which formed the seaward ends of the spurs were frequently damaged. Spur tips became separated from the main reef and formed outliers or were covered by sand and rubble. At the same time, grooves became longer and divided the reef crest zone. Examples of these losses are shown on Paynes Bay 1 reef (Figs. 2 and 4b) and on Cunards 2 reef (Fig. 5a).

The second type of loss involved the development of major breaches in reef fronts which appear to have been initiated by widening and deepening of the grooves. Grooves enlarged to form sand and rubble filled valleys which cut through the reef crest and invaded the back reef zone. Examples of these breach features are shown on Paradise Beach 1 (Fig. 3A) and Paynes Bay 2 (Fig. 4B) reefs.

Thirdly, large-scale losses on the flanks of several reefs – Paradise Beach 1 (Fig. 4A), Paynes Bay 1 and 2

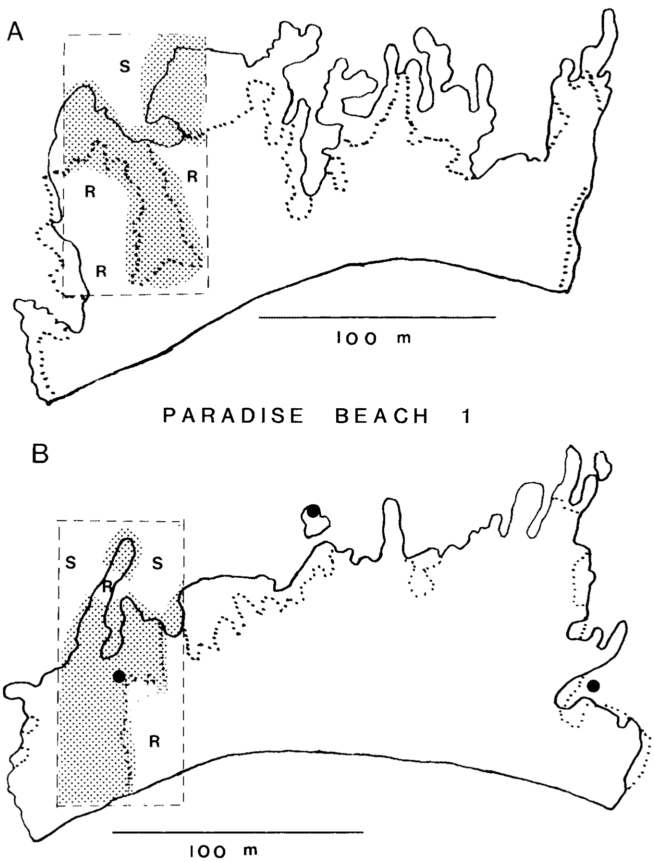


**Fig. 4.** Outlines of reefs traced from enlargements of 1950 and 1991 aerial photographs. **A** Paradise Beach 1; **B** Paynes Bay 1. *Solid lines* are 1950 outlines, *dotted lines* are 1991 outlines. *Dashed lines* enclose areas of field validation. *Stippled areas* are mixed sand and rubble substratum. *R* Reef surface; *S* sand bottom. *Solid circles* are visual reference coordinate points as on Fig. 2

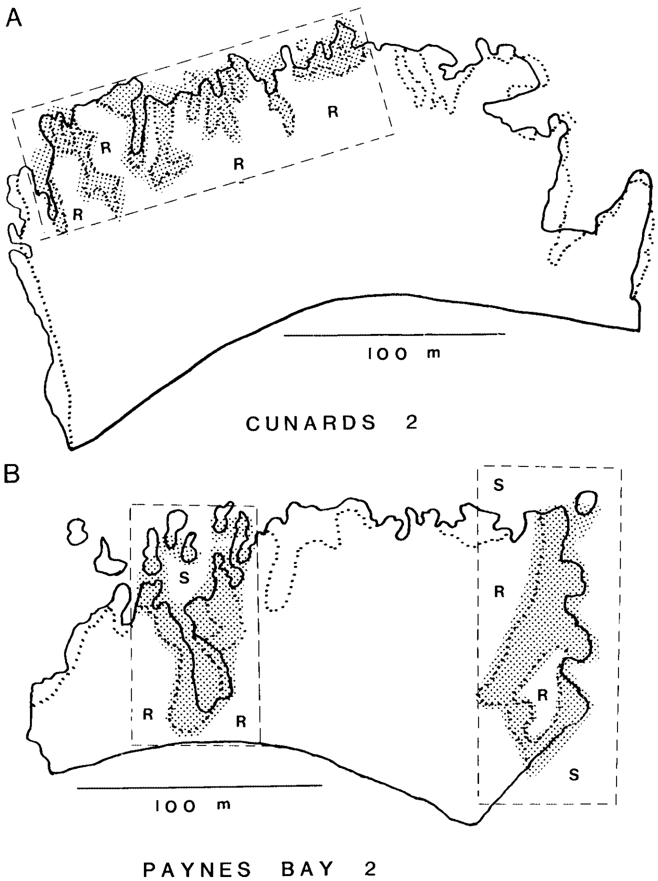


**Fig. 5.** Outlines of reefs traced from enlargements of 1950 and 1991 aerial photographs. **A** Cunards 2; **B** Paynes Bay 2. *Solid lines* are 1950 outlines, *dotted lines* are 1991 outlines. *Dashed lines* enclose areas of field validation. *Stippled areas* are mixed sand and rubble substratum. *R* Reef surface; *S* sand bottom

(Figs. 4B and 5B), and Six Mens (Fig. 6B) – were distinguished by the disruption of zonal patterns at the extreme ends of the reefs and replacement by sand and rubble. The consequence of damage on reef flanks was that affected reefs were shortened in length.

The causes of reef structural decline over a 40-year period may simply be the sum of natural and human environmental factors noted previously. However, because structural damage appears to be most intense along the exposed, frontal "spur and groove" zone, storm damage may be the most important single factor. Mah and Stearn (1986) and Scoffin (1994) reported that coral cover on the spur tops dropped dramatically following Hurricane Allen in 1980 and that dislodged rubble and sand were swept across the reef front and up and down the reef grooves. Thus it appears that structural losses in the "spur and groove" zone are due in part to earlier storm damage. Impairment of growth and lack of replacement of corals (Tomascik and Sander 1985, 1987) would also contribute to structural loss.

Similarly it can be argued that development of the long grooves and wider breaches in the central reef areas is strongly influenced by storm-generated erosive effects of unstable sand and rubble. Hubbard et al. (1994) reported that the fronts of southerly facing reefs at Buck Island in the US Virgin Islands were devastated by a hurricane which left homogenized rubble and sand that was ultimately deposited elsewhere on the reefs. Blanchon et al. (1997) have emphasized the fundamental importance of storm damage to reef architecture.

Area losses on the flanks of several reefs occurred in shallow water and were likely influenced by the impact of beach changes and sand movement. These positions were initially shallow and narrow in width and thus were exposed to erosion and smothering by beach sand. Bird et al. (1979) described how wave and current processes transported significant volumes of beach sand and caused marked seasonal changes in morphology of beach cells which lie at the ends of reefs and between reef sets.

In conclusion, the results indicate a significant loss of reef structure on eight of the 20 reefs, in addition to the superficial loss of coral communities. It is important, then, that further deterioration caused by human activities of the types reported by Tomascik and Sander (1985, 1987) be reduced. The situation is critical, for continued physical loss of the fringing reefs of Barbados

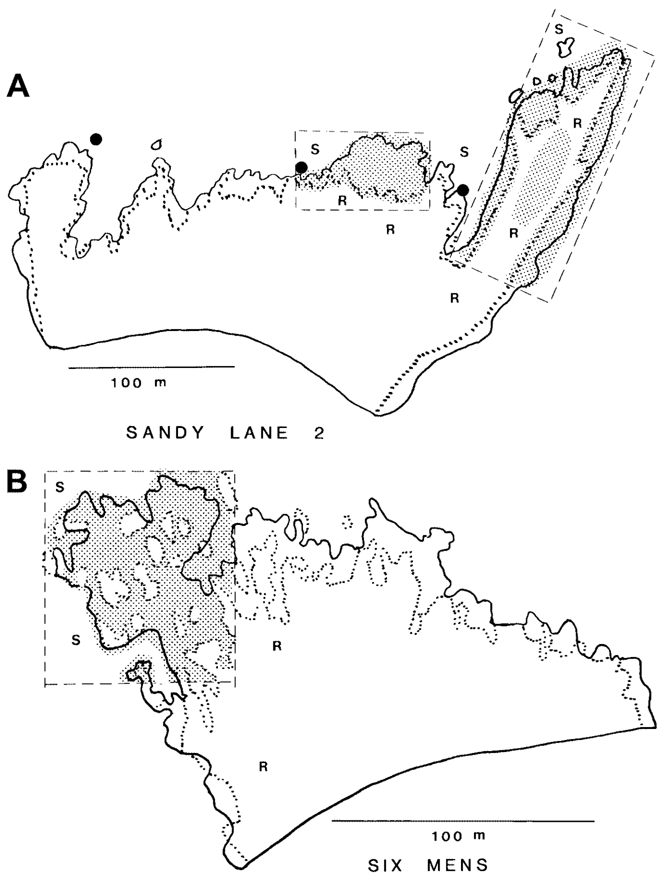


**Fig. 6.** Outlines of reefs traced from enlargements of 1950 and 1991 aerial photographs. **A** Sandy Lane 2; **B** Six Mens. *Solid lines* are 1950 outlines, *dotted lines* are 1991 outlines. *Dashed lines* enclose areas of field validation. *Stippled areas* are mixed sand and rubble substratum. *R* Reef surface; *S* sand bottom. *Solid circles* are visual reference coordinate points as on Fig. 3

will have serious ecological and economic effects upon beach conservation, fishing, and tourism.

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