BASELINE CONDITION OF THE CORAL REEFS AND FISHES
ACROSS THREE DEPTH ZONES OF THE FOREREEF OF BERMUDA

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B.R.E.A.M: Bermuda Reef Ecosystem Analysis and Monitoring Programme

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Synopsis

Bermuda's coral reefs protect our beaches and coastal properties from erosion, and high coral cover and abundant parrotfishes make our coral reefs healthy. Predatory fishes like snappers and rockfishes play a critical role in maintaining reef health by eating the kinds of fishes which damage corals and promote healthy herbivorous (plant-eating) fish populations. In this report, we provide clear evidence that historically abundant predatory fishes are rare and at critically low biomass levels on Bermuda reefs. The cover of corals remains high at forereef locations, but is lower at 30m depth, within the lagoon and particularly at nearshore reefs, where marine plants are overly abundant and plant-eating fishes are scarce. Long-term monitoring is required to determine whether reef condition is stable or in decline across the Bermuda reef system. Unless we better manage and protect our predatory reef fishes, the health of our reefs will decline, reef erosion will increase, and beaches and coastal properties will suffer substantial damage from increasing storm wave erosion in the coming decades.

Main Points

- Bermuda's coral reefs protect our beaches and shores from coastal erosion by storms and hurricanes, and provide appealing experiences for tourists.
- Bermuda's coral reefs are under threat from global climate change and ocean acidification.
- Coral reefs are most resilient to these serious threats when predatory fishes including groupers and snappers, and plant-eating parrotfishes and surgeonfishes are abundant.
- BREAM scientists measured the amount of corals, marine plants, plant-eating fishes and predatory fishes across all Bermuda forereef habitat in 2009 and 2011.
- We found that while corals and plant-eating fishes are abundant, predatory fishes are much rarer than they should be.
- Commercial and recreational fishing annually constitute only 0.7% of the economic value generated by the services provided by Bermuda's coral reefs to our society. Yet we manage the condition of our reefs as if they are primarily a fisheries concern.
- Reef condition is really a tourism and coastal protection issue, and should be managed accordingly.
- We can restore predatory fish populations by restricting the rate at which commercial and recreational fishers catch groupers and snappers, limit the sale of key predatory fishes during their spawning season, expand the seasonal prohibition and extent of protected spawning areas where necessary, and enhance marine resource enforcement.
- We can improve the resilience of our coral reefs by recognizing that additional marine protected areas are needed for certain species and habitats, such as our patch reefs and inshore reefs.
- If we ignore the critical loss of predatory fishes on our reefs, it is highly likely that our coral reefs will erode away. In an era of rising sea level, this condition will allow higher levels of storm wave impacts to threaten our coastal properties and beaches, while also reducing the visual appeal of Bermuda's waters to both visitors and locals.

Executive Summary

Bermuda is a 35 sq. km. limestone island located in the North Atlantic at 32º N 64º W; surrounded by 750 sq km of living coral reefs. In this report, we focus upon the forereef habitat. The forereef of Bermuda surrounds both the island and its lagoon and encompasses an area of 400 sq km. The coral-rich forereef extends from 12-ft (4-m) depth down to 120-ft (38-m) depth and beyond, although corals are sparse below 150-ft (45-m) depth. These coral reefs protect Bermuda from storms, enhance tourism experiences, generate sand for our beaches, and provide habitats for the fishes we like to eat.

Unfortunately, factors that operate on both a local and a global scale threaten the future of both our coral reefs and our island community. At a global scale, climate change is warming the ocean, which may cause an increase in the number and strength of storms and hurricanes. The rate at which reef corals are stressed, bleached, or are infected with diseases may be increasing, and marine plants (macroalgae) which can overgrow hard corals are prevalent on our reefs. Atmospheric carbon dioxide from fossil fuel combustion dissolves in the ocean, making it more acidic, which may cause coral reefs and the calcifying organisms that live on them to erode faster than they can grow. Local threats to reefs such as overfishing, coastal development, dredging, sewage disposal and the introduction of exotic species are harming coral reefs within small localized areas or across the island's entire reef system.

In order to determine the condition of the entire forereef, the scientists of the Bermuda Reef Ecosystem Assessment and Mapping Programme (BREAM) carried out over 70 quantitative reef surveys across the Bermuda forereef area in 2009 to 2011, looking at the abundance of 100 species of fish and over 35 measures of reef condition. In this report we describe the results of the baseline assessment of hard corals, fleshy macroalgae, herbivorous fishes and predatory fishes across the 10-m, 20-m and 30-m forereef zones. We compare these results with older BREAM datasets from the lagoon and rim reefs, and to similar surveys from Caribbean reefs, in order to provide a comprehensive assessment of reef condition for the entire Bermuda reef platform.

In this report we use a "Reef Life Score" (RLS) to grade the observed state of four critical biological components of reef condition that contribute fundamentally to the "ecological health" of each coral reef surveyed. These scores are then aggregated into a Sea Life Index (SLI) for each reef, and for the forereef as a whole. The four biological components that we scientifically assessed are the coverage of (1) Hard Corals and (2) Fleshy Macroalgae (marine plants), and the biomass of (3) Herbivorous (plant-eating) Fishes and (4) Predatory (fish- and animal-eating) Fishes at each site.

- Hard Corals are colonial animals, similar to sea anemones, but which build the limestone structure of coral reefs.
- Fleshy Macroalgae are marine plants that compete for space on the reef surface with Hard Corals, but do not build reef structure.
- Herbivorous Fishes eat Fleshy Macro-algae, which allows Hard Corals to dominate coral reefs. Parrotfishes and Surgeonfishes were the only herbivorous fishes counted in this category.

- Predatory Fishes, such as Groupers and Snappers, are critical regulators of other fish and invertebrates on reefs. Predatory Fishes come in two size classes: Large predatory fishes (e.g. black grouper) that eat smaller kinds of herbivorous fishes, which allows the more active large herbivorous fishes to dominate reefs and keep macroalgae in low abundance. Large predatory fishes also eat small predatory fishes, as well as other prey. Small predatory fishes (e.g. coney) eat damselfishes, which can kill coral. Species in the Predatory Fish category are targets of both commercial and recreational fishing across the entire reef lagoon and forereef, and down to 600 ft (200m) depth.

The Reef Life Score values used in this report match those in the "Reef Health Index" utilized by the Mesoamerican Healthy Reefs programme (Healthy Reefs Initiative 2012) that assesses reef condition across the Western Caribbean reef system that is connected across Belize, Guatemala, Honduras and Mexico. RLS values are calculated according to the following criteria for each of the four core metrics of reef condition:

The factors assessed for reef condition, and the assignment of Reef Life Score for each factor according to the observed range of values for each factor at each reef site.

Reef Condition	Critical	Poor	Fair	Good	Very Good
Reef Life Score	1	2	3	4	5
Hard Coral Cover (%)	< 5.0	5 – 9.9	10.0 – 19.9	20.0 – 39.9	≥ 40.0
Fleshy Macroalgae Cover (%)	> 25.0	12.1 – 25.0	5.1 – 12.0	1.0 – 5.0	< 1.0
Herbivorous Fishes (g.100m^{-2}) (Parrotfishes & Surgeonfishes)	< 960	960 – 1919	1920 – 2879	2880 – 3479	≥ 3480
Predatory Fishes (g.100m^{-2}) (Grouper & Snapper only)	< 420	420 – 839	840 – 1259	1260 – 1679	≥ 1680

Analysis of these four fundamental reef parameters allowed us to calculate the overall index of coral reef condition, the "Sea Life Index" (SLI), for each reef and depth zone of the 750-sq km coral reef system that surrounds the islands of Bermuda. The comprehensive SLI was calculated by aggregating the four Reef Life Scores (RLS) for each reef. The overall Sea Life Index, and the Reef Life Score for each component parameter, are affected by the amount of exposure to both natural and human-caused sources of stress and disturbance, as well as growth and resilience, that each reef site experienced in the time leading up to the survey.

Future assessment of the same RLS components will allow us to see how the condition of each reef and zone is changing through time. Additional monitoring of the factors that affect these reef conditions is also required if we are to link environmental or human causes to the ecological outcome of reef condition that is measured by the SLI.

As the Sea Life Index of each site is the average of the whole-number Reef Life Scores of the four component parameters, the values of the SLI for each ranking occur over the range of values that do not match those of the RLS components. The range of values for each SLI ranking are displayed below:

The range of aggregated RLS of the Sea Life Index that correspond to each reef condition.

SLI	Critical	Poor	Fair	Good	Very Good
Score Range	1.00 to 1.79	1.80 to 2.59	2.60 to 3.39	3.40 to 4.29	4.30 to 5.00

Key Findings

The key findings of reef and fish RLS condition and comprehensive SLI across Bermuda are tabulated below. Overall, our survey results show a system-wide lack of predatory fishes, low biomass of herbivorous fishes across the entire 20-m and 30-m zones, and high cover of fleshy macroalgae across the entire 30-m zone. High coverage of hard corals and generally low cover by fleshy macroalgae elsewhere across the forereef were also observed. The combination of all factors was used to determine the SLI of the forereef habitats. The SLI indicates only the 10-m forereef zone is in fair condition, but that the 20-m and 30-m deep habitats are in poor condition, based on the absence of predatory fishes, reduced number of herbivorous fishes and high macroalgae cover. Combined with prior results of nearshore fringing and lagoonal patch reef studies by the BREAM programme, it can be seen in the table below that Bermuda's reefs are in only fair or poor condition, platform-wide. This result conflicts with the popular opinion that Bermuda's reefs are relatively healthy, and instead indicates our reefs are potentially less resilient than has been assumed prior to this baseline assessment.

By completing the analysis of the forereef zones and adding the Sea Life Index scores from these zones to new scores calculated from the baseline data collected across the Rim, Lagoonal and Fringing reefs in previous BREAM surveys, we were able to present in this report the overall Sea Life Index score for the entire Bermuda Platform. The Bermuda Platform as a whole received at score of 2.69 overall, or "Fair".

Baseline BREAM data encompassing all of Bermuda's platform for 178 coral reefs and over 120 species of fishes is available at: http://www.bermudaBREAM.org

Reef Life Scores and Sea Life Index grades for each zone, and the Bermuda Reef Platform.

	Fringing Reefs	*Lagoonal Patch Reefs*	*Rim Reefs*	*MPA*	*10m Forereef*	*20m Forereef*	*30m Forereef*	**Bermuda Reef Platform**
Hard Coral RLS	*3.30 Good*	*3.83 Good*	*3.77 Good*	*4.17 Good*	*4.46 V Good*	*4.37 V.Good*	*3.50 Good*	**3.95 Good**
Fleshy Macroalgae RLS	*1.33 Critical*	*2.74 Fair*	*2.65 Fair*	*2.87 Fair*	*2.67 Fair*	*2.63 Fair*	*1.00 Critical*	**2.50 Fair**
Herbivorous Fishes RLS	*3.20 Fair*	*3.66 Good*	*4.07 Good*	*2.03 Poor*	*2.96 Fair*	*1.05 Critical*	*1.75 Critical*	**2.87 Fair**
Predatory Fishes RLS	*1.50 Critical*	*1.73 Critical*	*1.43 Critical*	*1.20 Critical*	*1.33 Critical*	*1.05 Critical*	*1.00 Critical*	**1.36** Critical
Cumulative Sea Life Index	**2.35 Poor**	**3.02 Fair**	**3.01 Fair**	**2.57 Fair**	**2.85 Fair**	**2.28 Poor**	**1.81 Poor**	**2.69 Fair**

Causes for Celebration

- Hard Corals are at Very Good or Good levels across most of the 10-m and 20-m deep reefs, and are Fair or better across all other inshore zones.
- Fleshy Macroalgae is in Fair levels across the 10-m and 20- deep reefs, as well as across the rim and lagoon.
- Parrotfishes, the dominant Herbivorous Fishes in Bermuda, were protected in 1993, and the populations appear to have recovered from the over-fishing which occurred in the 1980s. Parrotfishes and Surgeonfishes were at Good to Fair levels across the Rim Reefs, 10-m Forereef Zone and within the Lagoonal Patch and Fringing sites.

The 1990 “fish pot ban” legislation was forward-thinking and decades ahead of its time. Only now are the rest of the Caribbean islands working to enact similar limits to the fishing pressure on critical herbivorous fish species. Bermuda has very high densities of parrotfishes and other plant-eating fishes across the lagoon, rim and 10-m forereef. We did find low densities of parrotfishes and other herbivorous fishes at 20-m and 30-m depth, which strongly affected the SLI score in those zones. However, unpublished BREAM data shows that other types of herbivore, specifically small plant-eating snails and hermit crabs, are abundant at 20-m depth. It is likely these “micro-herbivores” are responsible for maintaining low levels of marine plants and promoted reef condition in a manner not observed using the methods of this study.

Causes for Concern

The system-wide and critical lack of predatory fishes across all zones is evident in our results. The pattern of critically low biomass of predatory fishes occurred at all zones, in both the lagoon, and on the forereef. The standard for assessing biomass of these predatory fishes is based on scientifically assessed historical levels of predatory fish biomass both in Bermuda (Bardach, 1959) and across the Caribbean (Healthy Reefs Initiative 2012). Overfishing in the 1970s and 1980s was the documented cause for the decline of predatory fishes on Bermuda reefs (Butler et al 1993). The recuperation of predatory fish stocks after the fish-pot ban of 1990 may be hampered by current commercial and recreational fishing pressures.

The overall capacity of Bermuda's reefs to grow and repair themselves from natural and human-caused impacts, called the reef's resilience to impact, is weakened by the lack of predatory fishes. All reef zones are impacted by this lack of predatory fishes. Commercial fishing relies on the predatory fishes to sustain the industry, and if the predatory fishes are overfished past their capacity to maintain their populations, through reproductive failure, then the industry will collapse again. Overfishing of the stocks of Nassau Grouper and several other species of groupers, now listed as protected species, has caused the industry to switch to other kinds of fishes, especially pelagic species, to maintain economic viability. The results of this in-water, visual-census-based study indicate that the remaining species of large and small groupers and snappers remain at a high risk of collapse due to their low abundance in all reef zones.

Herbivorous Fishes were seen to be at Critical (low) levels at both 20-m and 30-m depth. It is possible that this pattern of low abundance of parrot- and surgeonfish on the deeper forereef zones is a natural distribution pattern that has been in existence for a long time, and not indicative of a recent natural nor human impact to plant-eating fishes, but there is little historical data. Herbivorous fishes optimize their growth by grazing on plants that themselves grow fastest when well-lit and exposed to a high current flow. Deeper reefs experience lower light levels and less exposure to wave-based water flow, inhibiting some types of plant growth and thus providing lower-quality food for herbivorous fishes.

Fleshy Macroalgae were observed to be at Critical (high) levels on Fringing Reefs, which are located next to the shoreline of Bermuda. It is likely that marine plants are abundant in this zone due to anthropogenic land-based sources of dissolved nutrients, since herbivorous fishes were also observed to be abundant in the Fringing Reef zone. Land-based sources of nutrients, which include farming, golf courses and domestic sewage, can accumulate in ground water and flow into nearshore waters where they stimulate plant growth.

Fleshy Macroalgae were also observed to be at Critical (high) levels on deep forereefs at 30-m depth. The reefs at this depth are exposed to low light levels, which plants are better adapted to persist within relative to hard corals. It is likely that the pattern of high macroalgae abundance at the 30-m depth zone is due to the competitive advantage that plants have over hard corals in the low light in this zone. The SLI is designed to show both natural and manmade impacts to the four marine functional groups of species, and in the case of the 30-m zone, demonstrates how the natural stress of low light also affects the ecology of the reefs.

Recommended Management Actions or Changes to Policy

It is recommended that current or new management options are implemented to pursue the following two types of management strategy:

A. Restoration of reef predator populations

1. Enhance the stocks of groupers by introducing a limited ban on the capture and sale of Black groupers during their spawning period (as we currently do with spiny lobster), based on evidence of the timing of their maximum aggregation at spawning sites.
2. Consider bag and size limits on grey snappers, schoolmaster snappers, yellowtail snappers, graysbys and coneys.
3. Expand our knowledge of juvenile predatory fish habitats, which are generally within the lagoon (patch reefs), along the shore (nearshore), and within enclosed bays (inshore). Many species of offshore reef fish, including predatory fish species, start life by settling as juvenile fish to coastal habitats, only to move offshore as they mature.
4. Reduce coastal development impacts to the marine environment, as many juvenile predatory fishes are found the inshore and nearshore waters first before they move to outer reef areas.
5. Design coastal structures so that they provide additional habitat for juvenile and adult fishes. For instance, rough surfaces can be sculpting into dock surfaces or by construction with cobble, intertidal pools can be inset into dock surfaces, and clusters of thin vertical structures mimicking mangrove habitat can be installed under docks. These habitat supplements can increase the range of fish that live near built marine structures (reviewed in Murdoch 2013).

B. Develop marine spatial planning approaches for enhanced conservation benefits

Protected areas act as a marine resource “banks” and provide “interest” in the form of continuously available fishes for commercial and recreational harvest, through the spill-over effect, and enhanced reproductive output. We recommend the expansion in the distribution of protected areas to include inshore and coastal reef, mangrove and seagrass habitat, as well as areas of lagoonal patch reefs, for closure and protection. Research indicates the value of these marine areas as juvenile habitats, and their current threatened status due to a lack of smaller predatory fishes and high damselfish densities Damselfishes persistently attack corals and their populations can be controlled by increasing predator populations. Networks of lagoonal reefs that form continuous connections between habitats close to shore and outer reef habitats at the rim and forereef play an important role by allowing fishes to transition from zone to zone throughout their life cycle. In addition, networks of reefs support more biodiversity compared with isolated reefs.

Introduction

Bermuda's coral reefs (Fig. 1) are vital to the persistence of the island's economy, ecology and cultural wellbeing. Living coral reefs together form a self-healing protective sea wall, blocking 97% of the energy from storm waves (Lugo-Fernandez et al. 1998), which would otherwise destroy both our fragile limestone shoreline and the coastal infrastructure and houses we have built along its edge. Our tourism industry relies on the beauty and charisma of our island; contributed substantially by the many recreational and aesthetic opportunities provided by the coral reefs around us. An economic evaluation of the lagoonal reef, which represents half of the entire reef system, found that US$722,000,000 of goods and services are contributed annually to Bermuda's economy by the reefs of Bermuda (van Beukering et al 2009).

It is strongly in Bermuda's long-term best interests to ensure that the coral reef system that protects our island and sustains our lives is itself protected from the extensive harm that can be caused by deleterious human activities such as over-fishing, dredging, shipping traffic and the broader global environmental threats of climate change and ocean acidification (Smith et al. 2013)

Not only are our reefs critical to our survival, they are also fragile (Hoegh-Guldberg et al 2007). Coral reefs around the world have been in decline since the 1980s (Gardner et al 2003). In a recent report that examined the state of coral reefs across the entire Caribbean, including Bermuda, it was found that the vast majority of reefs are substantially altered relative to the state they were in 40 years ago (Jackson et al 2014). Coral cover, predatory and herbivorous fish populations have declined and fleshy macroalgae (reef plants) have increased at most locations across the Caribbean/Western Atlantic region. Bermuda was listed as one of only seven reef provinces in the region with moderately high coral cover, high biomass of herbivorous fishes and low reef cover of marine plants – indicating that Bermuda reefs had remained in generally good condition up to 2010, when the last surveys were taken for that report. However, the report also determined that predatory fishes were found to be rare in Bermuda, as in most Caribbean countries (Bermuda chapter in Jackson et al 2014).

Despite the seemingly good condition of Bermuda's reefs and fishes relative to those of the Caribbean, Bermuda's marine environment is subjected to a range of natural and anthropogenic threats (Table 1 reviewed comprehensively in Smith et al 2013). Threats can be categorized according to source. Local threats are those that happen within the outer boundary of the Bermuda reef platform, and are from impacts that generally can be managed by changing people's behaviour. Global threats, alternatively, occur across the planet due to changes in atmospheric and oceanic concentrations of pollutants such as carbon dioxide which result in climate change and ocean acidification.

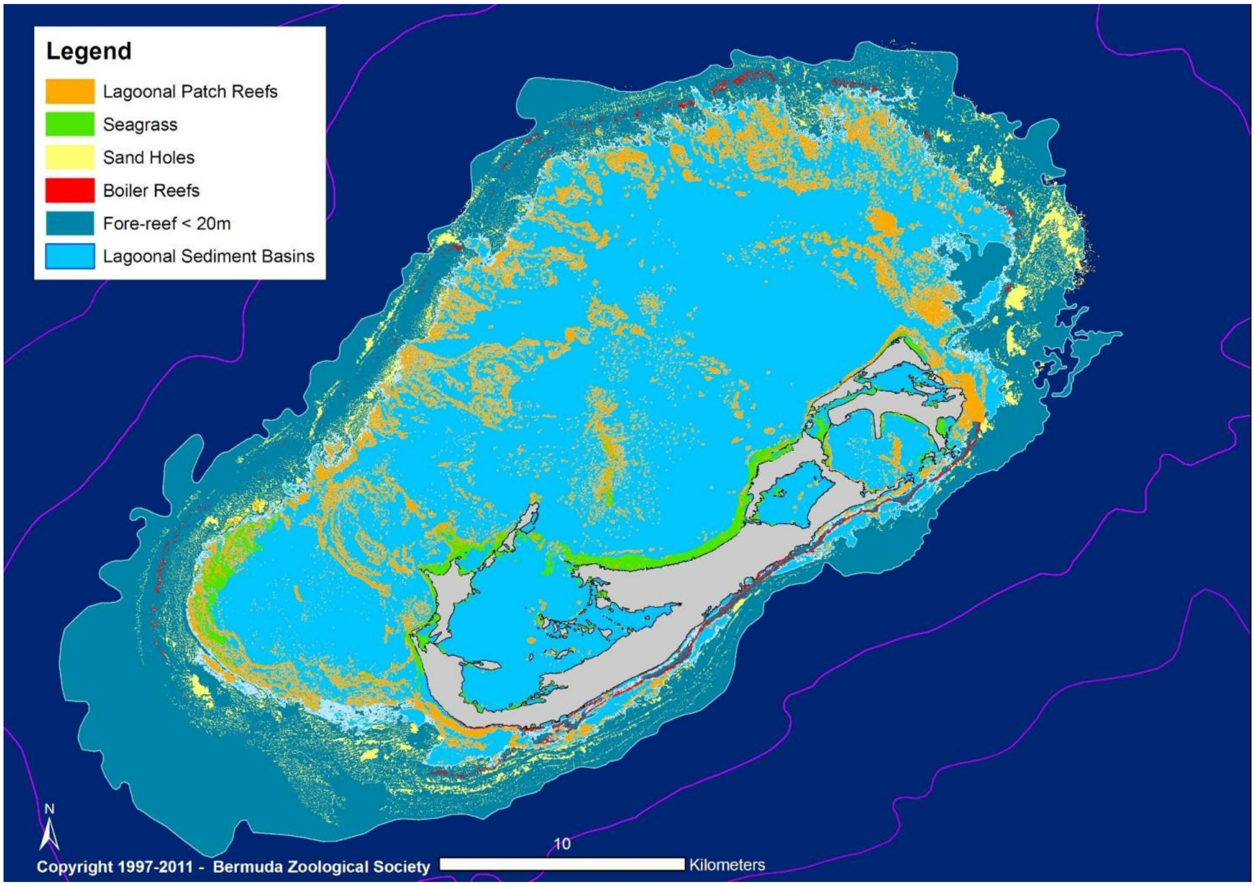

Fig. 1. Through GIS mapping of a high-resolution aerial mosaic of photographs, the BREAM lab charted all seagrass meadows, lagoonal patch reefs, boiler reefs, forereef sand-holes and sediment basins across the Bermuda platform (BREAM 2011).

Table 1. Potential and known threats to Bermuda's reef system

Local Threats:
1. Over-fishing or over-harvesting
2. Dredging of channels
3. Sedimentation created by shipping traffic through channels
4. Coastal development
5. Ship and boat groundings
6. Marine diseases affecting corals and fishes
7. Coral bleaching cause by above normal or below normal water temperatures
8. Chemical pollution from land run-off, marine activity and dumping
9. Marine debris, particularly plastic trash
10. Invasive species, such as lionfish
Global Threats:
11. Climate change, resulting in a warming ocean that stresses marine life, increases the rate of occurrence and strength of storms, and causes sea level to rise
12. Ocean acidification, resulting from higher carbon dioxide levels, which can slow coral growth and speed up erosion

In order to limit the impact of local and global threats to coral reef condition and the abundance of reef fishes, it is critical that Bermuda manages the anthropogenic sources of threats and mitigates damage caused to reefs by natural threats. To properly manage a reef system, there is a need to:

1. Obtain information of the baseline condition of the reef system if it is not known. Baseline information is collected through activities that include:
   A. Mapping reef locations accurately, so that the extent and layout of the habitat is known.
   B. Assessing the status (i.e. abundance, biomass, relative cover, and other parameters) of ecologically important fishes and benthic organisms, such as herbivorous fishes and corals, across the entire reef platform.
2. Monitor the changes in key resilience factors, such as reef growth, parrotfish density or hard coral and marine algae cover, which may change from baseline and cross thresholds that indicate decline through time
3. Inform the public, resource managers and policy makers of the state of the reef and fishes, so that local impacts can be managed, through changing people's behaviour, or by modifying territorial regulations.
4. Develop a set of effective management and conservation actions that target and resolve specific changes in the condition of the reefs and their associated biota, so as to preserve or enhance ecosystem function.

To directly address the lack of quantitative information about the state of our coral reefs and associated marine ecosystems that existed up to 2000, the Bermuda Reef Ecosystem Assessment and Mapping Programme (BREAM) was started as part of the Bermuda Biodiversity Project (BBP), and then formally named as a stand-alone research programme in 2004. Prior to the initiation of the BREAM programme, Bermuda reefs were not mapped nor assessed for baseline information on the condition of fishes, corals nor other biota across the entire platform in a comprehensive, quantitative manner. Previously, reef locations were assessed by researchers who were focussed on a limited number of environmental or biological parameters and who carried out their research at a small collection of sites. Single reef sites of ~100-m^2 or less were used to determine the coral assemblage structure of entire reef zones measuring 10s to 100s of sq km in area.

In this report we document the baseline ecological condition of the forereef habitat of Bermuda, as assessed by a series of survey sites around the Bermuda platform at 10-m, 20-m and 30-m depth, from 2009 to 2011. The forereef habitat is composed of the coral reefs that are found on the seaward side of the shallow "rim" reef that surrounds both the island and the lagoon of the Bermuda platform (Fig. 1). The forereef zone includes the "reef terrace", which is a broad flat shelf found between 20-m and 35-m depth particularly on the western, northern and eastern sides of the Bermuda platform. A 10- to 20-m high underwater precipice is found along at the 25- to 45-m depth contour along the southern side of the Bermuda platform.

Previous studies by BREAM documented the baseline condition of coral reefs across the lagoon and shallow reef rim around

Bermuda (Murdoch et al 2008, Hammond et al 2008), and the baseline condition of seagrass habitats across the platform (Murdoch et al 2007a, 2007b). The baseline data of marine habitats collected in the BREAM programme suite of projects will be used to guide the long-term monitoring of the entire Bermuda platform by the BREAM team, in conjunction with the citizen-science initiative Bermuda Reef Watch (Murdoch 2013, 2014a, 2014b, 2015). The Bermuda Reef Watch project teaches the public about reef and fish ecology and enables them to collect information on reef ecological condition across the lagoon on a yearly basis. This report intentionally focuses on the same parameters of reef condition that are used in the Bermuda Reef Watch programme, and the ecological parameters of reef condition that we studied in the making of this report are hopefully familiar to the public, resource managers and policy makers.

While not the focus of this report, we collected a broad range of information regarding the size, condition and species distributions of both adult and juvenile corals, coral diseases and other biological sources of impact, as well as the abundance or biomass of several other kinds of benthic biota including soft corals and sponges, as well as ~100 species of fishes. The raw data from these surveys are collated in a comprehensive database that is available online via www.bermudaBREAM.org**.** The analysis of the separate components of the large complex dataset will be presented in a series of additional BREAM reports as part of the Bermuda Biodiversity Project at the Bermuda Aquarium, Museum and Zoo.

The ecological condition of Bermuda's forereef ecosystem has never been comprehensively surveyed in a quantitative manner prior to this project, in part due to the vast area under study (~750 sq km). Coral reef surveys that encompassed entire regions were rare across the world until the 1990s, due to both the logistical challenges that the fieldwork entailed, and the limitations of desktop computers at the time. Assessment across a nested suite of spatial scales of the Florida Keys Reef Tract by the Keyswide Coral Reef Expedition (Murdoch and Aronson 1999), and the Australian Great Barrier Reef (Hughes et al 1999), both in 1995, and a smaller study in the US Virgin Islands in 1994 (Edmunds and Bruno 1996), demonstrated conclusively that the important indicators of reef or fish population condition in large coral reef systems vary in a complex and patchy manner over a range of spatial scales. This high degree of patchiness across spatial scales indicated that it was impossible to know the condition of a large reef system by assuming that a few small-scale samples were representative of the broad area. Instead, it is likely that each large coral reef system possesses its own scales of spatial variability and that the management of large reef systems must be guided by the collection of baseline data and continuous monitoring over the entire expanse of the region (Murdoch and Aronson 1999, McField and Kramer 2007). Concurrently, the World Resources Institute released in 1998 the "Reefs at Risk" map-based indicator analysis of the potential threats to the world's coral reefs (Burke et al 1998), which showed that most of the world's coral reefs were under threat or already in decline. Many countries were starting or expanding their baseline data and monitoring efforts by 2000.

One of the standardized methodologies utilized by many countries to assess their reef systems was the Atlantic and Gulf Rapid Reef Assessment (AGRRA) protocol (AGRRA 2005; www.agrra.org).The AGRRA monitoring and data-warehousing programme was initiated in 1998, with the goal of developing a protocol for the rapid assessment of coral reefs across broad, regional spatial scales from country to country across the Western Atlantic. A preliminary set of AGRRA surveys was carried out across the Bermuda platform by the Bermuda Biodiversity Project team in 1998, following the production of the BZS aerial photomosaic of the entire Bermuda reef platform in 1997. The preliminary AGGRA data has not been published, but is archived in the Bermuda Natural History Museum at BAMZ. Baseline AGRRA assessment of Bermuda's coral reefs by BREAM began in 2004, with one mega-transect of sites running from nearshore to the rim in the Western Lagoon and one mega-transect of sites across the North Lagoon. The entire lagoon was assessed at 45 sites in 2005, and 25 sites located around the shallow rim reef of Bermuda were surveyed in 2006. The benthic information from these first 3 years of surveys were documented in Murdoch et al (2008), with the fish data reported in Hammond et al (2008). The Murdoch et al (2008) report covers the rest of the shallow reef habitat where hard corals are abundant. Below 30-m depth are found the mesophotic coral reef communities, characterised by low light conditions, which results in both low coral cover and low rates of reef growth when compared to the more ecological and geologically active shallow reef system.

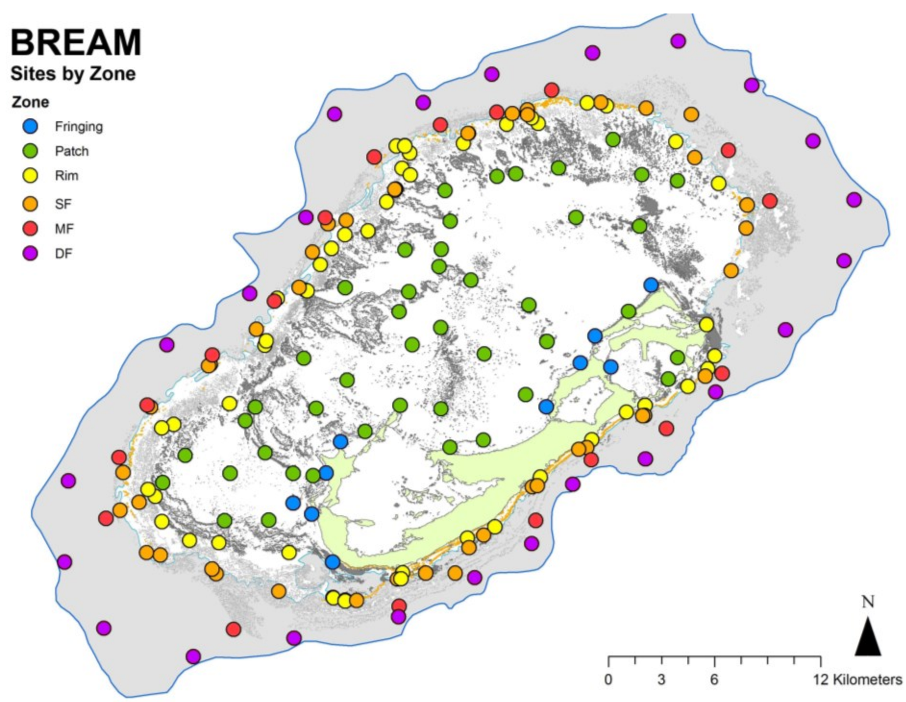

Fig. 2. Location of the 178 AGRRA and REEF benthic survey sites completed across the Bermuda Reef Platform from 2002 to 2011. Fish and benthic community structure were assessed at each point. Sites are colour-coded by zone. Forereef sites are labelled as SF: Shallow Forereef (10-m), MF: Middle Forereef or terrace (20 m) and DF: Deep Forereef (30 m). The outer blue line illustrates position of the 200-m depth contour.

Methods

Survey Sites

Coral reef habitats and associated biota were assessed by teams of research divers on SCUBA using air or Nitrox at 24 Buoyed Marine Protected Area (BMPA) sites at a range of depths and reef zones in 2009 (Fig. 3, Table 2), 24 sites at 10-m depth (Fig. 4, Table 3), and 19 sites at 20-m depth in 2010 across the Bermuda forereef (Fig. 5 , Table 4), using a version of the Atlantic and Gulf Rapid Reef Assessment (AGRRA) protocol #4.0 (www.agrra.org), modified by our research group to suit the ecology of Bermuda's reefs. An additional 25 sites were surveyed at 30m depth in 2010 (Fig. 6, Table 5) with the use of a high-definition video drop-camera array that we designed and built for the task.

The two BMPA sites not surveyed were the Xing Da and the Vixen cultural marine protected areas. Xing Da was excluded due to its depth, which exceeds -35m. The Vixen wreck was not surveyed as it is heavily visited by tour boats, the fishes are fed, and it is located in the sand-covered pass between two reefs.

The BMPA sites were all surveyed in the summer and fall of 2009. In all cases 6 benthic transects were placed haphazardly within 50 m of the marker buoy at each site by a team of 2 or 3 divers. The 10-m and 20-m forereef sites were selected haphazardly to be between 3.75 and 4.25 km apart and at the correct depth range and near a sand hole large enough to permit the safe use of a Danforth-type anchor by one or two island boats. The 10-m and 20-m sites were surveyed during June – December (summer and autumn) of 2010, with a few 20-m sites surveyed in March (winter) of 2011. The 30-m sites were surveyed in May - June, 2010.

Since BMPAs consist of both natural areas and areas characterized by ship wrecks of different ages, and since BMPAs are found across a range of zones, the factors affecting the ecological patterns found within BMPA are different to those of the natural forereef sites also assessed in 2009-2010. These factors will be examined in a separate report, and we do not discuss the BMPA further here. Raw data for the BMPA are included in the Appendices and online database.

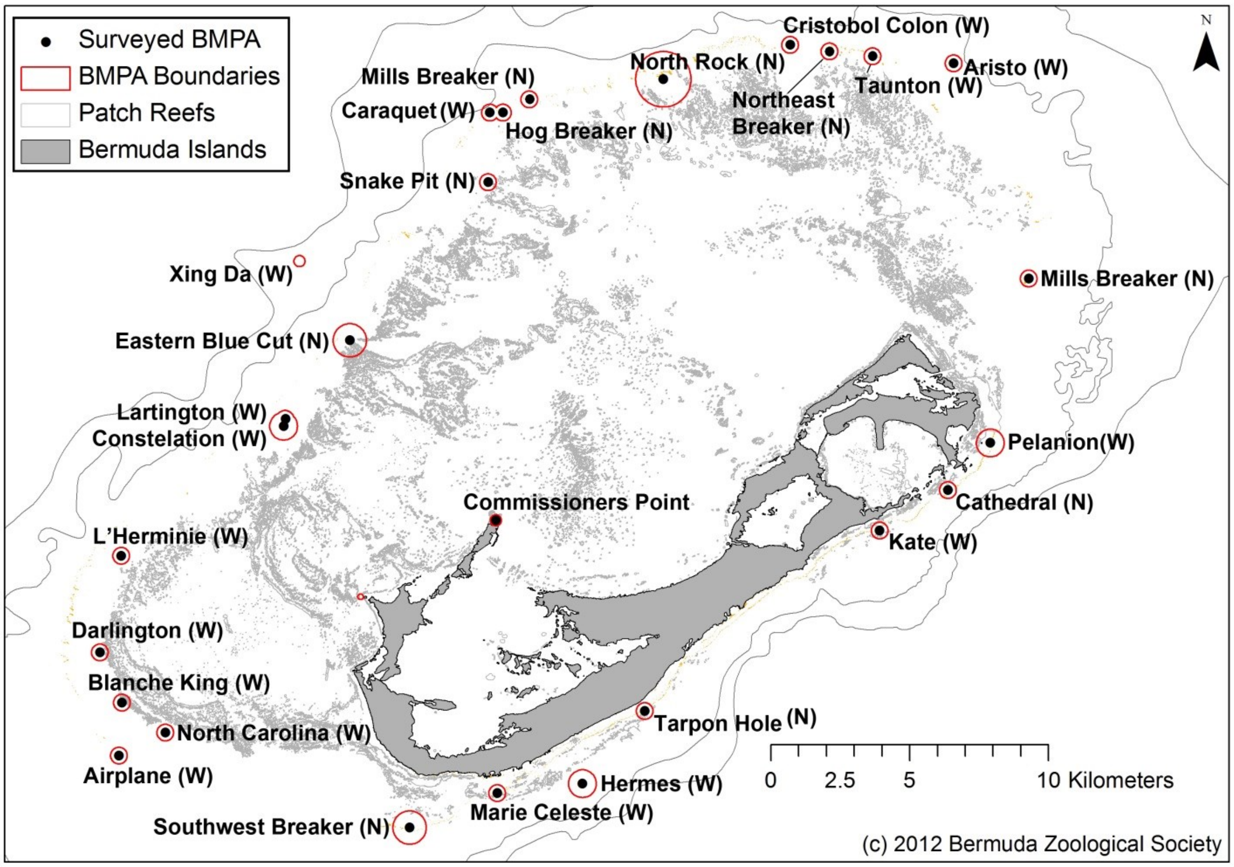

Fig. 3. Map of the Buoyed Marine Protected Area (BMPA) site locations, and the size of each BMPA boundary. BMPA sites characterized by a shipwreck are labeled (W), while natural sites are labeled (N).

Table 2. Location information for the Buoyed MPA sites surveyed

BMPA	Name	Latitude	Longitude	Habitat	Depth (ft)	Natural or Wreck	Sector
1	Aristo	32.4791	-64.6573	Fore	45	W	E
2	Mills Breaker	32.4092	-64.6286	Rim	16	N	E
3	Pelinaion	32.3558	-64.6434	Rim	10	W	E
4	Cathedral	32.3405	-64.6596	Rim	10	N	S
5	Kate	32.3273	-64.6965	Rim	30	W	S
6	Tarpon Hole	32.2688	-64.7757	Rim	30	N	S
7	Hermes	32.2452	-64.7995	Fore	60	W	S
8	Marie Celeste	32.2421	-64.8321	Rim	40	W	S
9	SW Breaker	32.2309	-64.8656	Rim	25	N	S
10	North Carolina	32.2616	-64.9591	Rim	20	W	W
11	Airplane	32.2541	-64.9768	Fore	30	W	W
12	Blanche King	32.2713	-64.9757	Rim	20	W	W
13	Darlington	32.2876	-64.9842	Rim	20	W	W
14	L'Herminie	32.319	-64.9761	Rim	20	W	W
15	Commissioner's	32.3307	-64.8327	Patch	5	N	L
16	Lartington	32.3635	-64.9132	Rim	30	W	N
17	Constellation	32.3612	-64.914	Rim	30	W	N
18	Eastern Blue Cut	32.3891	-64.8887	Rim	10	N	N
19	Snake Pit	32.4405	-64.8358	Rim	10	N	N
20	Hog Breaker	32.4631	-64.8301	Rim	20	N	N
21	Caraquet	32.4631	-64.8351	Rim	30	W	N
22	Madiana	32.4583	-64.8083	Rim	30	W	N
23	North Rock	32.474	-64.7686	Rim	10	N	N
24	Cristobal Colon	32.4851	-64.72	Rim	40	W	N
25	Northeast Bkr	32.4833	-64.7083	Rim	30	N	N
26	Taunton	32.4917	-64.6917	Rim	30	W	N

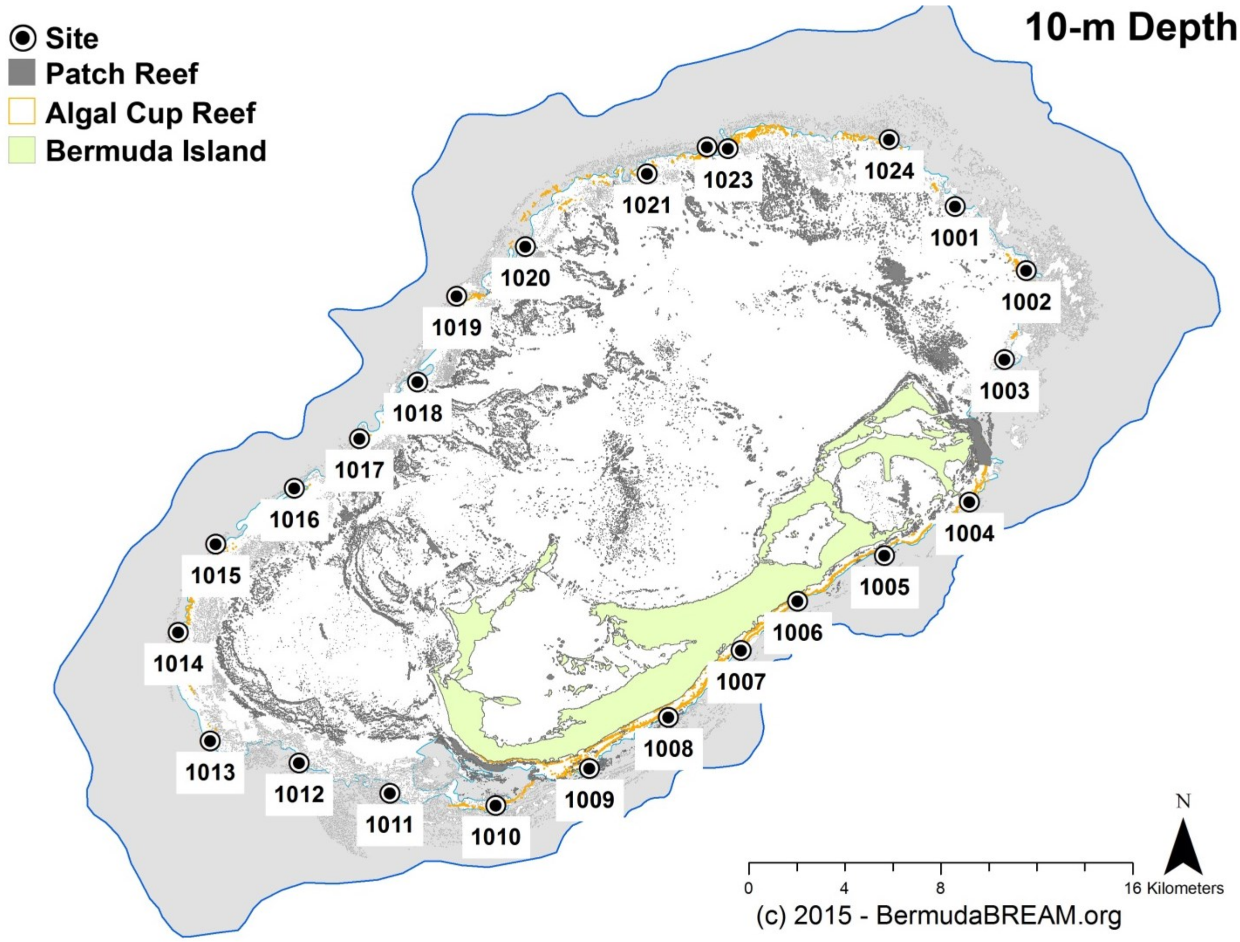

Fig. 4. A map of the 24 baseline coral reef sites located at 10-m depth surveyed by the BREAM team in 2010.

Table 3. The site numbers, names, Latitude, Longitude and zonal designations for the 24 sites of surveyed by BREAM at 10-m (30-ft.) depth in 2010.

Site	Name	Latitude	Longitude	Sector
1001	NNE 30	32.45706	-64.6554	E
1002	Kitchen 30	32.43296	-64.6238	E
1003	Mills 30	32.39941	-64.6335	E
1004	Coopers Island 30	32.34566	-64.6492	S
1005	Kate 30	32.32541	-64.6867	S
1006	Spittal 30	32.30824	-64.7251	S
1007	Hungry Bay 30	32.28969	-64.7502	S
1008	Elbow 30	32.26445	-64.7824	S
1009	Horseshoe 30	32.24514	-64.8172	S
1010	SW Breaker 30	32.23115	-64.8586	S
1011	Chaddock Bar 30	32.23574	-64.9055	W
1012	Little Bar 30	32.24709	-64.9456	W
1013	W Ledge 30	32.25532	-64.9849	W
1014	Chub Head 30	32.29622	-64.9993	W
1015	Long Bar 30	32.32950	-64.9827	N
1016	Chub Cut 30	32.35063	-64.9480	N
1017	Lartington 30	32.36940	-64.9191	N
1018	EBC 30	32.39092	-64.8935	N
1019	Angel 30	32.42317	-64.8762	N
1020	Snake Pit 30	32.44200	-64.8360	N
1021	Dark Slime 30	32.46947	-64.7919	N
1022	E. North Rock 30	32.47955	-64.7652	N
1023	Reel Sticky Reef 30	32.47900	-64.7560	N
1024	NE 30	32.48236	-64.6845	N

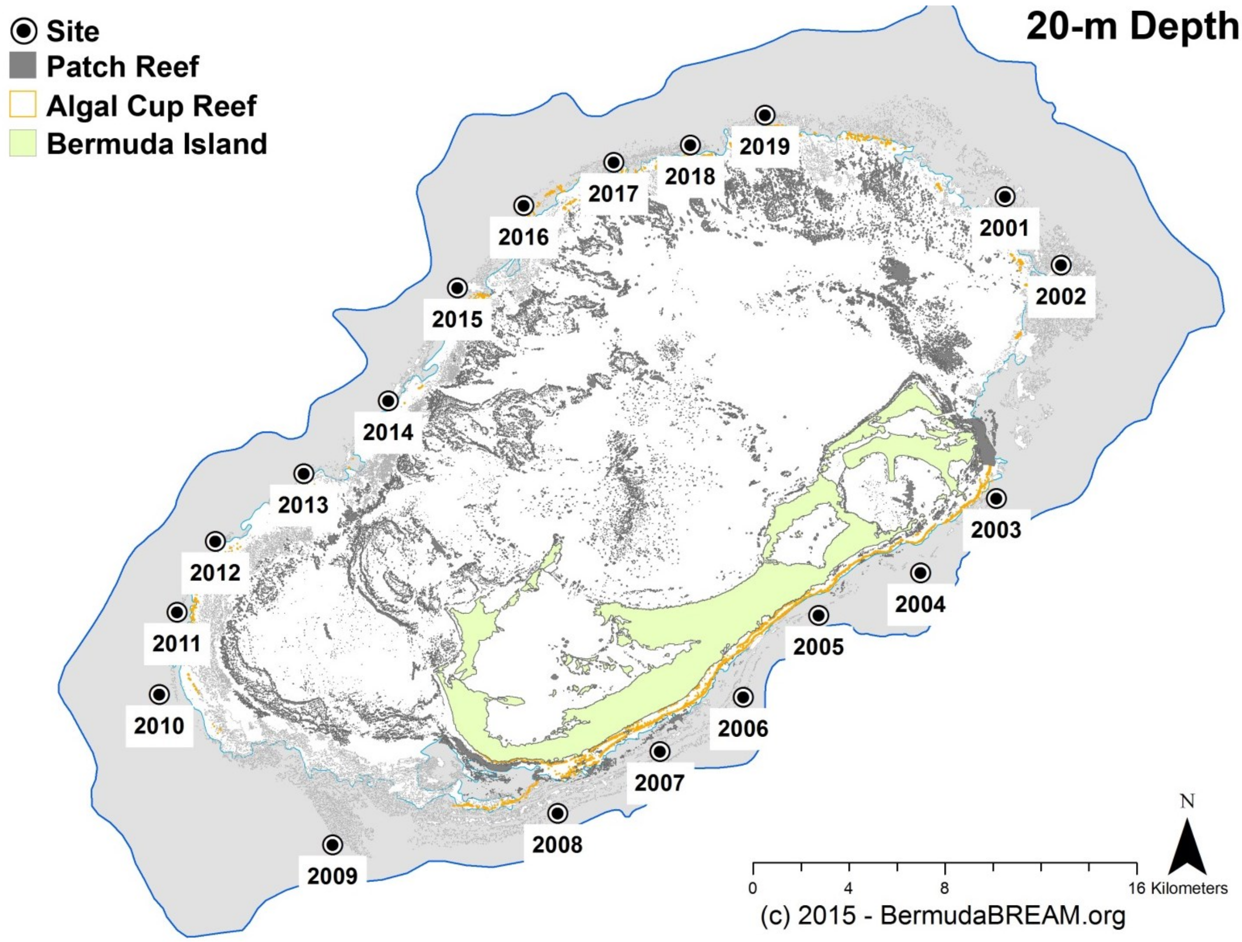

Fig. 5. A map of the 19 forereef sites surveyed at 20m depth.

Table 4. The locations and sectors of the 19 sites surveyed at 20-m (60-ft) depth.

Site	Latitude	Longitude	Sector
2001	32.4608	-64.6349	E
2002	32.4350	-64.6102	E
2003	32.3470	-64.6390	S
2004	32.3189	-64.6725	S
2005	32.3030	-64.7177	S
2006	32.2720	-64.7510	S
2007	32.2375	-64.3713	S
2008	32.2282	-64.8332	S
2009	32.2163	-64.9327	S

Site	Latitude	Longitude	Sector
2010	32.2728	-65.0094	W
2011	32.3039	-65.0017	W
2012	32.3306	-64.9848	W
2013	32.3562	-64.9458	W
2014	32.3837	-64.9084	W
2015	32.4264	-64.8778	N
2016	32.4575	-64.8484	N
2017	32.4737	-64.8086	N
2018	32.4803	-64.7746	N
2019	32.4916	-64.7415	N

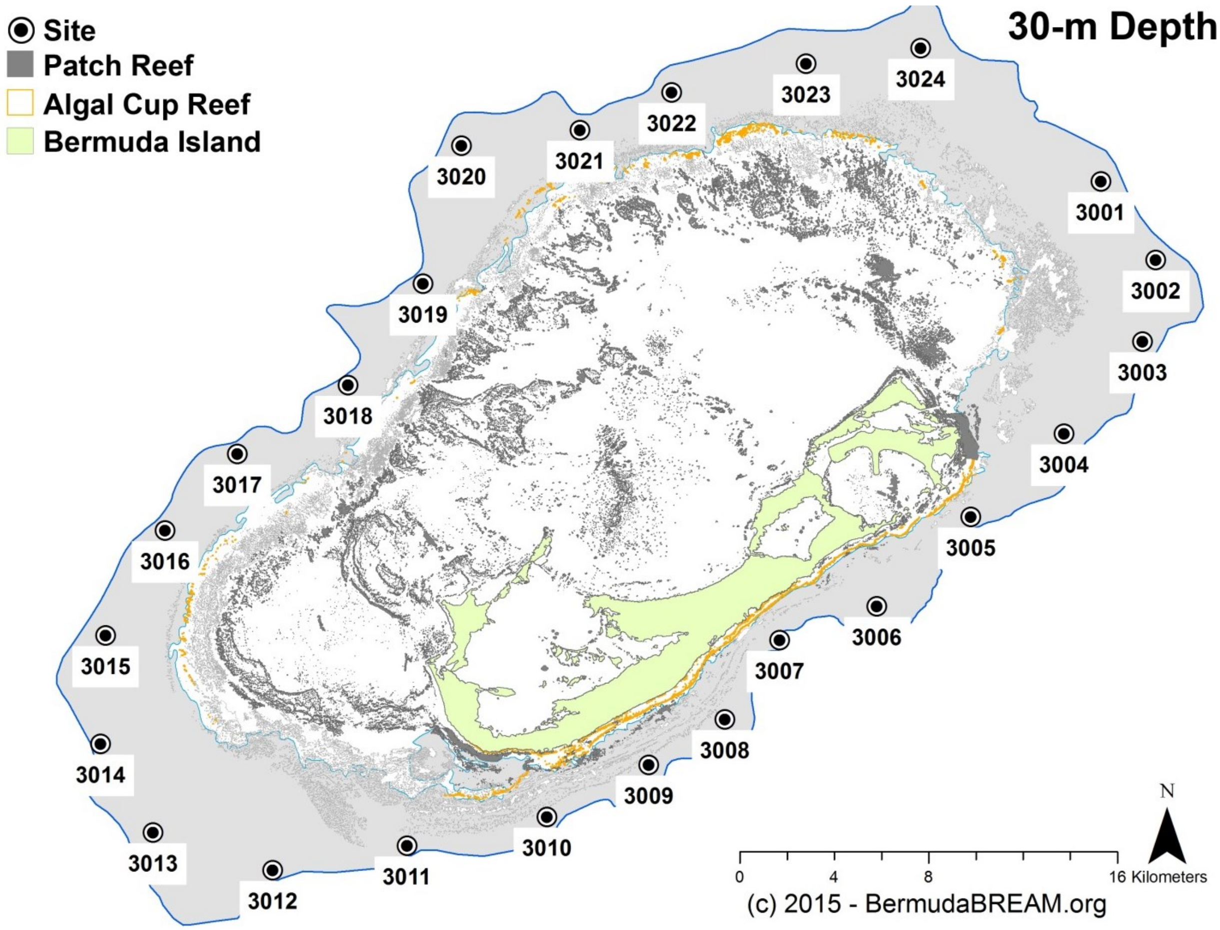

Fig. 6. A map of the 30-m depth forereef survey sites assessed by video drop camera array.

Table 5. Site locations and zonal designations for the 30-m deep survey sites.

Site	Latitude	Longitude	Sector	Length
3001	32.46549	-64.5841	E	410 m
3002	32.43543	-64.5593	E	620 m
3003	32.40438	-64.5654	E	500 m
3004	32.36917	-64.6008	E	520 m
3005	32.3375	-64.6429	S	950 m
3006	32.30335	-64.6851	S	385 m
3007	32.29037	-64.7288	S	905 m
3008	32.26015	-64.7535	S	580 m
3009	32.24275	-64.7877	S	500 m
3010	32.22293	-64.8334	S	350 m
3011	32.2118	-64.8964	S	300 m
3012	32.20232	-64.9567	W	380 m

Site	Latitude	Longitude	Sector	Length
3013	32.21664	-65.0106	W	805 m
3014	32.25053	-65.0342	W	515 m
3015	32.29197	-65.0322	W	460 m
3017	32.36138	-64.9731	W	550 m
3018	32.38772	-64.9231	N	360 m
3019	32.42655	-64.8895	N	460 m
3020	32.47914	-64.8722	N	315 m
3021	32.48513	-64.8189	N	580 m
3022	32.49961	-64.7775	N	1080m
3023	32.51063	-64.7169	N	480 m
3024	32.51647	-64.6651	N	520 m
3025	32.49394	-64.621	N	577 m

AGRRA protocol

At each of the BMPA, 10-m and 20-m sites, AGRRA benthic assessments of coral, algae and other benthic biota were made following Version 4.0 of the methodology, with local modifications as described below. In brief, sites were assessed in the following manner: 10-m transect lines, marked at 10-cm intervals, were laid on the reef surface from a haphazardly determined starting point. Linear-point intercept (LPI) data was collected from each transect by counting the number of each of the 100 points marked on each transect for the following categories of benthic functional group: Hard Coral, Sand, CTB (crustose coralline algae, bare rock, turf algae), FMA (fleshy macroalgae), CMA (calcareous macroalgae), GST (Gorgonian, Sponge, Tunicates).

The data listed below were then recorded for any stony coral colony underlying the transect that were of 10 cm length or greater in any dimension:

i. Species of coral
ii. Length of coral colony under the line,
iii. Maximum length,
iv. Perpendicular width
v. Height of coral colony
vi. Coral Health (disease, bleaching, damselfish bites, parrotfish bites)
vii. Partial Mortality of Colony: percentage of live tissue cover of the entire colony, as seen from a planar view (measured to the nearest cm for corals <100 cm and to the nearest 5 cm for corals ≥100 cm),
viii. Coral disease
ix. Coral bleaching
x. Damselfish damage
xi. Major overgrowths or other obvious causes of coral mortality

Coral cover for each site was determined in two separate ways. Linear point counts provided cover under each 10-m transect from the 100 points assessed visually in the survey. The length under the line of each coral colony along the 10-m transect also provided overall coral cover and species-specific coral cover data. We used the LPI data from each transect, plotted by box-plot to illustrate the variability within each site. Average percent coral cover of all transects at each site was used to calculate the Hard Coral Index of each surveyed reef location.

By assuming each coral was a halved section of an irregular ellipsoid (spheroid), following Thomsen (2004), the three dimensions measured for each coral in the AGRRA methods allowed us to calculate the surface area of each coral (i.e. the maximum length, perpendicular length and colony height, in cm), using the following formula:

$S » (4p [(a^pb^p + a^pc^p + b^pc^p) / 3]^{1/p)}/2$
with +/- 1.061% error when p »1.6075

The above formula can be used in a spreadsheet application as follows:

```
=4*3.1429*(((((((([Max Diam]/2)^1.6075)*(([Perp Diam]/2)^1.6075)))+
(((([Max Diam]/2)^1.6075)*([Max Height]^1.6075))+((([Perp Diam]/2)^1.6075)
*([Max Height]^1.6075)))/3)^(1/1.6075))/2
```

Supplemental data were collected at five points at 2-m intervals per each transect, starting at the 1-m mark and using a 25 x 25 cm quadrat. These data included substrate type, heights and coverage of fleshy and calcareous algae, dominant algal species, and number and species of stony coral recruits per quadrat. The abundance of the endemic herbivorous hermit crabs (*Calcinus verrilli*) and the native herbivorous reef snail (*Cerithium litteratum*) were also counted in each quadrat. The long-spined sea urchin (*Diadema antillarum*) and damselfish territory presence (but not damselfish species identity per territory) along the transects were also recorded (AGRRA, 2005).

Concurrent with coral and algae assessments, fish assemblages were assessed with AGRRA surveys (AGRRA.org) between the hours of 10 AM and 5 PM Atlantic Daylight Savings Time. Fish were enumerated by two SCUBA divers, conducting a total of ten 30-m long, 2-m wide belt transects per site. Transects were laid haphazardly and away from other divers to minimize any bias related to diver-activity. While surveying, divers swam slowly in one direction while an attached spool of transect line unravelled to signal completion of the transect. Any fish encountered within a lane bounded one metre on either side of the transect and upwards to the surface was counted and assigned to one of six visually-estimated total length categories (<5 cm, 5-10 cm; 10-20 cm, 20-30 cm, 30-40 cm, and >40 cm; AGRRA, 2005). Fish counts by size for each fish species were converted to species biomass in grams per 100 m^2 following the length-biomass conversion formulae listed in Appendix Two of Lang (2003).

To ensure coverage of less abundant fish species, which may not have been recorded on diver transects, the REEF Roving-Diver Technique was also employed by two divers during surveys. This protocol involved a timed period of swimming observation for over 30 minutes, where all fish species seen were recorded. Species were then categorized by abundance and recorded as "Single" (1 fish), "Few" (2-10 fish), "Many" (11-100 fish) or "Abundant" (>100 fish; REEF, 2007).

AGRRA Data Analysis

Univariate analysis of AGRRA coral cover data and fleshy macroalgae data was used to assess the range of benthic cover across sites, and to generate the benthic component index value for both parameters. Data on the biomass of herbivorous fishes (parrotfishes and surgeonfishes) and predatory fishes (groupers and snappers) were collected from the ten 30-m long by 2-m wide transects. The maximum, 75^{th}percentile, median (50^{th} percentile), 25^{th} percentile and minimum statistics of the percent cover data from the six benthic transects and ten fish transects assessed at each site at the 10-m and 20-m were calculated, and used to generate box-plots of sites for each zone. Since the project is exploratory, not hypothesis-based, box-plots were graphed instead of site averages and standard errors, and analyses of variance within or across depth zones were not calculated. Box-plots better illustrate the variability in the data within and between sites; which is more useful for the documentation of baseline condition.

Video Drop Camera Methods for 30 m forereef surveys

In order to survey the benthic and mobile biota at 30-m depth, we developed and produced a high-definition (HD) video drop-camera array. Replicate pairs of HD digital video cameras in underwater housings were mounted on an internal frame structure that also supported four high intensity underwater lights (Fig. 7). Two cameras and the four lights pointed towards the sea floor surface (Fig. 8), while the other two cameras without lights faced forwards(Fig. 9). An additional analogue (low resolution) camera faced forwards at a 45° angle towards the sea floor. This analogue camera was attached via a waterproof cable to a video monitoring and recording system in the R/V Endurance on the surface, and was used by the team of researchers to visually control the array so that it remained at a constant height above the sea floor surface of ~1 m during deployment. The entire camera array was contained in a rounded cylindrical fiberglass housing, which was designed to ensure the drop camera array would not become ensnared in jagged rocks should the array contact the reef surface. The housing was weighted and fitted with fins to ensure it would maintain a forward aspect while a transect was being filmed. The array and housing were connected to the R/V Endurance via a rope and pulley system, through a davit, in such a manner that one operator could hold the array and raise or lower the array to maintain optimal distance from the sea floor surface (Fig. 10).

Fig. 7. Four underwater camera housings (blue) and 4 underwater lights (black), mounted on the aluminium frame which will be inserted into the drop-camera housing. An analogue camera was also mounted onto this same frame below the uppermost video housings.

Fig. 8. A ventral-side photograph of the completed drop-camera array housing, constructed from a fiberglass water pressure tank. The 4 rectangular UW lights and two circular downward-facing HD video camera ports can be seen. The housing is sitting in a stand, and a pvc pipe supports a tail-fin. Side fins were added to reduce yaw. Weights were later added to the underside to further stabilize the array.

Fig. 9. A front-view of the camera housing. The two upper holes will allow two forward-facing circular HD video cameras to film fish assemblages as the array moved through the water over the reef. The lower circular hole is for the analogue video camera, which provides a live video feed to the researchers so that the camera array can be raised and lowered by rope to avoid objects while underway.

Fig. 10. Research technicians lowering the drop-camera array into the water. During filming, a separate video cable was also connected to the drop camera array separately.

The drop camera operator was guided in this activity by a second operator who watched the live video feed from the analogue camera, displayed on the video system inside the cabin of the R?V Endurance. A third operator recorded the depth as read by sonar at 1-minute intervals. The location of the array was recorded via a GPS unit which output location data onto an overlay of the analogue video footage, which was recorded onto a digital video hard drive. All four HD cameras recorded digital video data onto self-contained digital memory cards, which were removed and backed up after each transect was completed.

Transects were haphazardly located at 4.5-km intervals along the 112.5 km reef system at 30-m depth (Fig. 6). At each site, duplicate recordings of a single video transect were filmed over a 350-m to 500-m long swath of reef. Deployments were only carried out on days with very calm wind conditions. Transect direction was primarily determined by boat drift, which was generally at less than 1 kt. The sites along the South Shore were characterized by an underwater cliff that started at ~37-m (125-ft.) depth and ascended steeply or vertically to ~25-m (75-ft.) depth. The ~30m (90-ft.) depth contour was on the side of this cliff, and therefore we filmed transects that covered the expanse of the cliff from the top to the bottom. In cases where the boat drift was not parallel to the face of this underwater cliff structure (Sites 3007 to 3010), the transect was filmed in multiple sections after the research vessel repositioned itself. The sections of transect were treated as one whole transect in analysis. At all the other sites on the east, north and western sectors of the Bermuda platform the forereef was very flat at 30-m (90-ft) depth, and the direction of each transect at each site was determined by the manner in which the wind and currents carried the vessel.

The video cameras used in the drop camera were enclosed in plastic housings that were rated to 150-ft depth. However, we discovered that many of the housings had a manufacturing flaw that lead to the housing developing a fracture at depth – flooding the plastic housing in some cases. The cameras were enclosed in a soft silicone sub-housing within the outer plastic housing, which allowed some cameras to survive flooding in some cases. However, two cameras were flooded over the course of the project, which meant that at some sites only one copy of each transect was filmed from a single downward (benthic) camera and one forward facing (fish population) camera. The manufacturer replaced the flooded cameras and housings after the project was completed.

To collect data on the structure of the benthic habitats, digital video transects from the downward facing cameras were digitized to generate sets of high-resolution video frames (e.g. Fig. 11). Each 60-seconds of video was composed of 30 frames, and all frames from each transect (representing a site) were first digitized into separate still image files, using A4 Video Master Pro software (www.a4video.com). The intent was to then subdivide each transect into sets of frames that represented 1-m intervals, based on the time to film each transect and the length of each transect across the sea floor as recorded by the GPS unit. However, since the drop-camera array was suspended off the sea floor by 30-m or more of rope, and the array generated drag, the whole array was found to swing in a regular pendulum fashion while it was filming the reef. Also the surface of the reef was very rough, so the camera array had to be constantly raised and lowered to maintain a constant depth. For both of these reasons many of the framed grabbed from the HD video were taken at moments when the camera was moving quickly. Despite the high light provided by the high intensity UW lights, which allowed each video camera to use a high shutter speed with each frame, the high-motion frames were often too blurry to use. Since each transect represented 45 minutes to 60 minutes of footage, or 81,000 to 108,000 image files, we were left with either hand selecting each clear frame, which occurred when the array was momentarily motionless in the water while swinging, or to try to determine some manner of extracting the high quality frames from each data set.

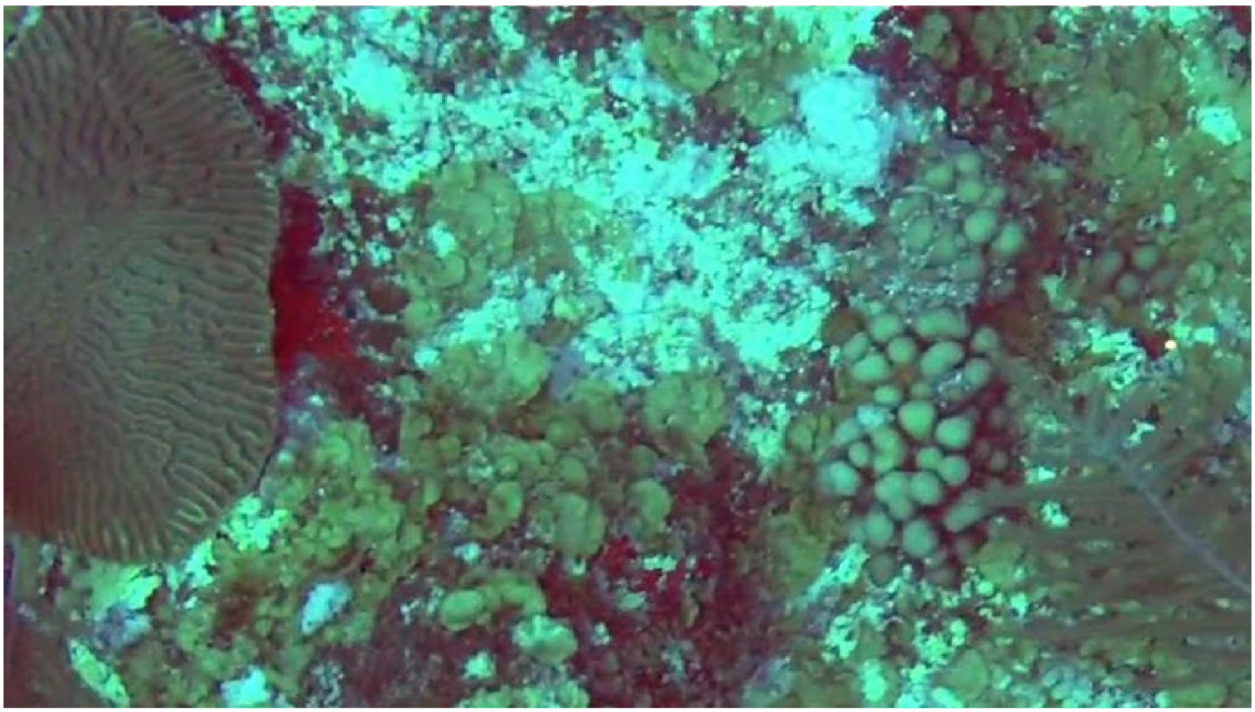

Fig. 11. A low-resolution version of a still frame of high-definition video, captured from footage recorded from a coral reef at 30-m depth. The field of view is ~50-cm wide. Objects of ~2-mm could be seen in most video frames from the 25 sites.

To extract the best frames from each video transect, we converted all the video frames from a raw file storage format to a JPEG format. JPEG format uses a fractal image compression algorithm, which means that a simple image with little texture or complexity can be saved as a small file, while highly textured, complex images such as those created when photographing a coral reef with a camera that is not in motion, are saved as a large file size. Unfortunately the contents of each clear image from the reef footage was different, and different objects in the set of images resulted in files of differing sizes, even when they were all clear sharp images. We developed a file-size filter algorithm that we could run in Excel that queried the file size of each consecutive image, and then selected locally large files from the range of file sizes. This allowed us to basically select the local peaks in file size, which were always the sharpest images filmed over a 10-20 second period (Fig. 12). By filtering the files in this manner we were able to reduce each image data set from ~100,000 image files down to 300-500, depending on the length of each transect.

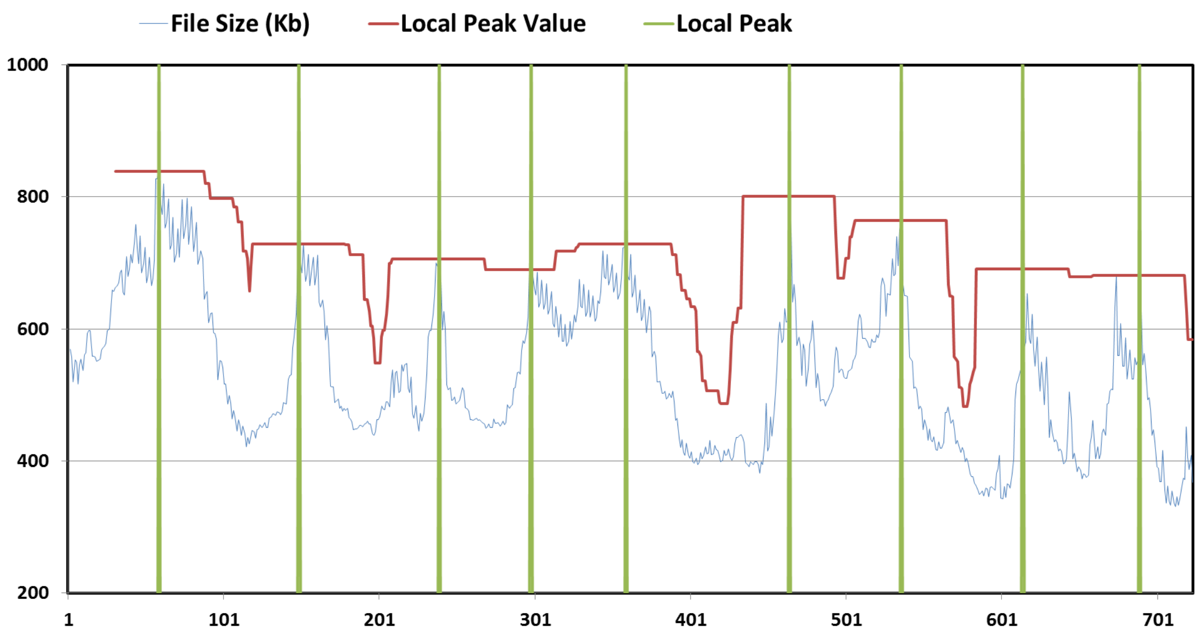

Fig. 12. A visualization of how we mathematically filtered the set of high definition video frames to select the optimal images from each transect. Image file numbers are on the X-axis and file data sizes are on the Y-axis. The blue line is a graph of the JPEG-compressed file sizes of the first 715 image files from a video transect. The sharpness of each image and the contents of each image affect the file size, with sharper images of complex objects being larger than images captured when the camera was in motion or was filming a simple background. This resulted in a jagged landscape of image file sizes with local peaks and valleys, complicating the selection of optimal files from the batch. The red line represents the value of local peaks in file size based on a local maximum filter. By trial and error we were able to select a filter width that allowed us to determine which files were of optimal quality out of each batch of ~100 frames from ~3 seconds of footage. The selected file number is marked by the green vertical bar, but taken from a spreadsheet table in the working analysis.

Video frame analysis of benthic assemblage structure

Video frames were processed to the highest taxonomic resolution possible using Coral Point Count with Excel extensions software (CPCe; Kohler and Gill 2006). 25 points were plotted in a random grid pattern in each frame. Each transect was of a different length and composed of a different number of frames. The area of substrate that was captured within each frame also varied in an unmeasured manner, although all frames were captured from footage from the drop camera filming at consistent relative depths of approximately 1-m .

Video frame data of the benthos was analysed differently from the AGRRA data collected at 10-m and 20-m depth. Boxplots were generated based on the range of values calculated from the 25 points within each photo-quadrat.

Video analysis of fish abundance

We counted all fish within the field of view of the forward facing HD cameras, estimating the size of each fish by comparing it to other objects in the field of view. Abundance data by size was used to calculate a single biomass value for each species and each guild for each site. Fish data was normalized by transect length to represent biomass per 100-m length. Transect width was variable but maintained to be as consistent between transects as possible by maintaining the drop-camera height between 0.5 and 1.5-m above the sea floor.

Defining reef condition with Reef Life Score and the Sea Life Index

In this report we focused on four indicators of the ecological condition of the Bermuda forereef habitat and associated biota. These four indicators are:

1. Hard Coral cover (percent cover of rocky reef substrate),
2. Fleshy Macroalgae cover (percent cover of rocky reef substrate),
3. Biomass of Herbivorous Fishes of the parrotfish and surgeonfish families (grams per hectare),
4. Biomass of Predatory Fishes of the grouper and snapper families (grams per hectare).

Each of these four factors contribute fundamentally to overall reef condition, and represent the core of a larger set of ecological factors which have been demonstrated through >60 years of research by the scientific community to contribute to the overall condition and resilience of coral reefs (e.g. McField and Kramer 2007, Mumby et al 2014). The baseline relative cover or biomass of these four biological components of reef ecology, when combined, provide a metric of both overall reef condition and reef resilience to future declines in condition from natural or anthropogenic impacts. When assessed over time, changes in the four factors can be used to indicate whether the reef under study is undergoing the improvement or deterioration in reef condition.

Not only is the ecological condition of each surveyed reef represented by the state of each of the four factors, a summary index we call the "Sea Life Index", which combines the separate levels of each of the four factors, can give an overall metric of reef health. No single factor contributes to overall reef condition nor the resilience of a coral reef against future disturbances on its own, and the combined index represents this concept of shared contribution and the need for all four components of reef condition to be at satisfactory levels for the overall reef condition to also be considered to be at a good or "healthy" state.

We selected the four indicators, and the correspondence between indicator value and relative condition, to match the Simplified Integrated Reef Health Index (SIRHI) used by the coral reef scientists of the Healthy Reefs research programme (Healthy Reef Initiative 2012, www.heathyreefs.org) who monitor the Meso-American coral reef system (McField et al 2011). We intentionally also use the same four indicator factors in the Bermuda Reef Watch programme for citizen scientists in order to assign the Reef Watch lagoon reef sites a health score, although the simplified assessment methods used by the Reef Watch programme necessitated using different kinds of data to calculate the Sea Life Index used in that programme (Murdoch 2013, 2014a, 2014b).

The parameter value for each indicator is used to define a Reef Life Score for each parameter at each study site. The parameter values from each indicator are also combined to form the Sea Life Index (SLI) number that indicates the ecological health of each reef site overall. Values for the Reef Life Score for each separate parameter are classified as "Very Good", "Good", "Fair", "Poor", or "Critical" based on the assessed values in four biotic components of reef condition (Table 6). The upper and lower bounds of each indicator were defined in McField et al (2011). Baseline status at each site across the different zones of the reef can thereby be graded, with reefs in Poor or Critical condition likely indicating the occurrence of some form of disturbance or stress. Future monitoring through time will also be able to plot the status of each reef site and the overall reef system according to the SLI number, with increases in SLI indicating improved ecological condition and declines in SLI indicating that local or global impacts are affecting reefs and that management actions may be needed. Each factor indicates specific forms of disturbance, interactions with other components of the ecology of the reef, and the specific approach in which resource management or impact mitigation will have to take for the reef to be restored to a more favourable state.

The range of values of each of the four Reef Life Score components of the Sea Life Index used in this report match the "Reef Health Index" scores utilized by the Mesoamerican Healthy Reefs programme (Healthy Reefs Initiative 2012). Values are calculated according to the following criteria for each of the four core metrics of reef condition.

Table 6. A table of the correspondence between Reef Condition, Reef Life Score, and the range of values for each of the four biotic components of the Sea Life Index.

Reef Condition	**Critical**	**Poor**	**Fair**	**Good**	**Very Good**
Reef Life Score	**1**	**2**	**3**	**4**	**5**
Hard Coral Cover (%)	< 5.0	5 – 9.9	10.0 – 19.9	20.0 – 39.9	≥ 40.0
Fleshy Macroalgae Cover (%)	< 25.0	12.1 – 25.0	5.1 – 12.0	1.0 – 5.0	< 1.0
Herbivorous Fishes (g.100m^{-2}) (Parrotfishes & Surgeonfishes)	< 960	960 – 1919	1920 – 2879	2880 – 3479	> 3480
Predatory Fishes (g.100m^{-2}) (Grouper & Snapper only)	< 420	420 – 839	840 – 1259	1260 – 1679	> 1680

Hard Coral Cover

Hard coral cover represents the primary factor that is indicative of coral reef health: coral reefs are, by definition, constructed by populations of hard corals. Hard coral cover denotes the percentage of the substrate that is covered by living hard coral tissue. Hard coral cover can be assessed in a variety of different scientific methodologies that include linear-point intercept and either in-situ or photographic quadrats (e.g. Rogers et al 1994, Mumby et al 2014).

Reef corals are colonial animals similar to sea anemones that contain tiny symbiotic dinoflagellate marine plants within their tissue. Reef corals capture food from the water column and also the symbiotic plants can produce sugars from photosynthesis that provide energy for their coral hosts. Reef corals build reefs by secreting a non-living calcium carbonate skeleton under the thin layer of surface tissue that forms the covering of the coral colony. Through time the shared contribution of the growth, death and accumulation of many coral colonies can build entire reefs covering many hundreds or thousands of square kilometres. Bermuda's shallow reefs were only formed after being submerged by the last sea-level rise about 7000 years ago (Fairbanks 1989), but overlay older geological outcrops created by reefs hundreds of thousands of years ago (Scoffin and Garrett 1974).

Healthy reefs are those that have a high proportion of the reef surface covered by living hard corals (e.g. Fig. 13) Reef growth is sustained by coral growth, which needs to progress at a rate greater than erosion caused by environmental and biological factors. Storms, waves and currents pick up sand, which abrades the surface of the reef. Many types of animals, including sponges and bivalves live by burrowing into the hard reef rock created by corals. Most parrotfishes scrape the reef surface, generating sand, while carrying out their important job of eating sea weeds (marine plants that grow on the reef).

The Reef Life Score for the cover of reef corals are assigned as follows: Coral reefs with 40% or more of the surface covered in hard coral are considered to be in "very good" condition, and are likely to display a high degree of topographic complexity and substantial amounts of biological diversity. Reefs with over 20% coral cover are considered to be in "good" condition, and are predicted to produce more reef rock than is removed by erosion. "Fair" reefs with 10 – 20% hard coral cover will probably persist, but are not growing any faster than they are eroding. Poor reefs have between 5 - 10% coral cover, and are probably eroding faster than they are growing. Finally, "Critical" reefs, with less than 5% living coral surface, are likely to be experiencing exceptionally damaging effects from either environmental or biological factors that are likely to cause substantial reef erosion and degrade the reef into a flattened state in less than a decade.

The "poor" and "critical" reefs are likely to be very flat, harbour low numbers of fishes and a reduced biodiversity, and will eventually erode down to the level of the surrounding sand beds unless conditions change in a way that allow new corals to establish on the reef and start the growth of new structure.

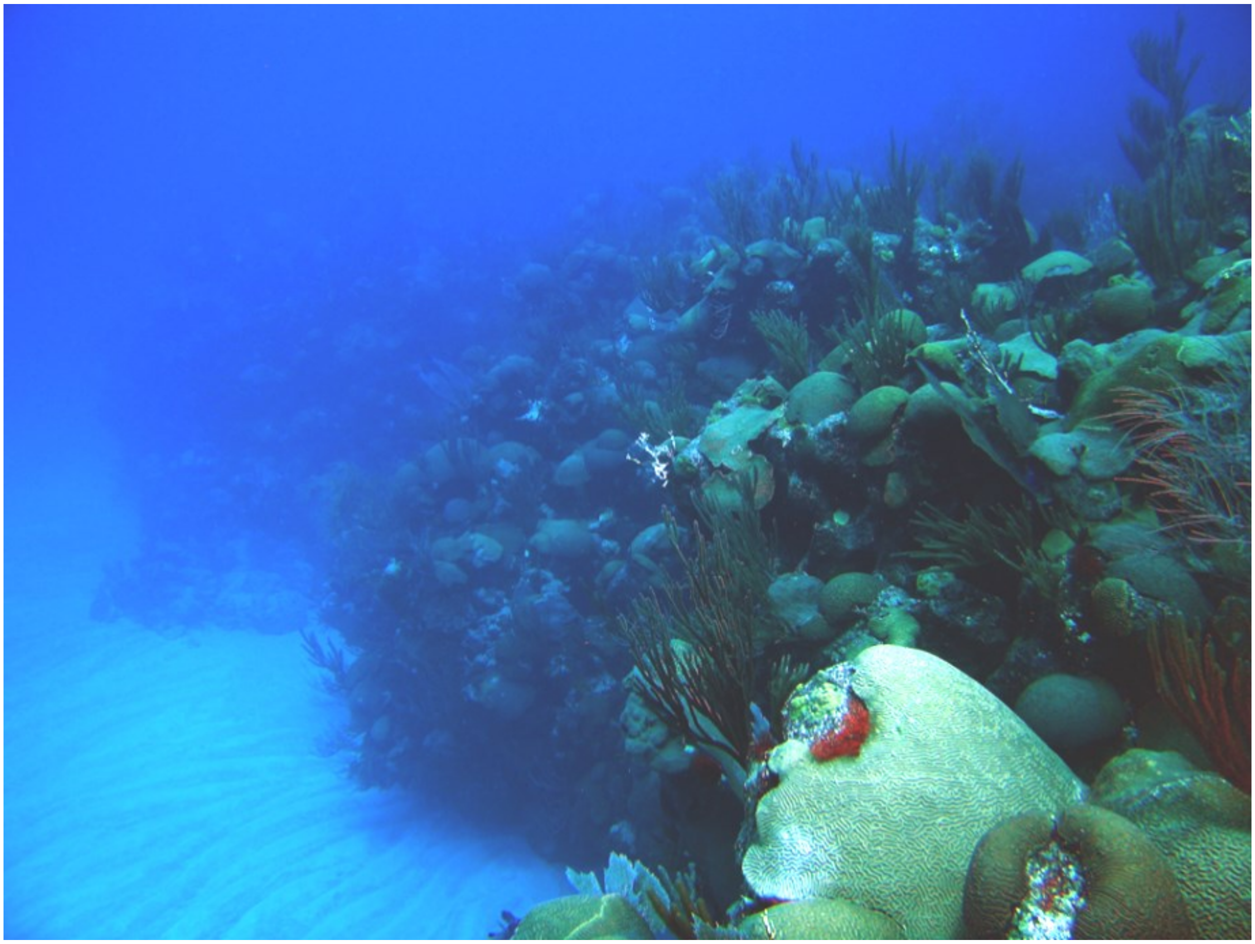

Fig. 13. Reefs with lots of corals, such as this 10-m forereef near Elbow Beach, Bermuda in 2009, grow more than they erode, building structural complexity which allows more species of fish, shellfish and other reef dwellers to find places to live

Fleshy Macroalgae

Fleshy macroalgae (FMA) are marine plants. Many species of marine plants live on coral reefs, and they are a natural and important part of the coral reef community. Marine plants provide food for a great many plant-eating fishes and other animals, a habitat for many small animals to live, and some marine plants produce carbonate material that contributes to reef structure. High coverage of marine plants is indicative of an unhealthy coral reef as lots of plants means that either there are not many plant-eating fishes or other animals on the reef to keep the marine plants in check, or there are high levels of nutrients on the reef with provide fertilizer to the marine plants and also which chemically inhibit the ability of hard corals to produce their skeletal structure which builds reefs (Fabricius 2005). Like hard corals, FMA also use sunlight to grow on the surface of coral reefs, but they do not produce calcium carbonate skeletons and as a result do not help build reef structure. Reef plants also use the same space on the reef that could be used by hard corals, and reef plants can negatively affect hard corals, and may damage or kill them in the process of competing for space.

Reefs that possess a high coverage of FMA are considered to be in poor health (e.g. Fig. 14), as reef growth is inhibited and the plants are preventing hard corals from colonizing or growing on these reefs. The Reef Life Score for the coverage of fleshy macroalgae were assigned as follows. We classified reefs with more than >25% FMA cover as "critical", and reefs with 12 - 25% FMA cover as "poor" reefs (Table 6). Reefs with between 5% and 12% FMA cover generally have enough surface area remaining for healthy hard coral growth, and are in "fair" health. Reefs are considered to be in "good" condition if they have very low seaweed cover of less than 5%. Reefs with less than 1% FMA are considered to be in "very good" condition.

Fig. 14. This reef located near Ely's Harbour has very high seaweed cover, indicative of poor ecological health. High rates of erosion have removed most structural complexity, resulting in fewer places for fish to hide and reducing the ability of the reef to protect the shore from storm waves.

Herbivorous Fishes

Parrotfishes in high levels of abundance can maintain reefs in a low macroalgae state when at least 40% of the surface is hard corals or another non-plant substratum, other than bare rock (Williams and Polunin 2001). Following McField and Kramer (2008), we classified reefs with over 3480 g per 100-m^{-2} herbivorous fishes as in "very good" condition on the Reef Life Score for herbivorous fishes. Reefs sustaining 2880 – 3479 g per 100-m^{-2} of herbivorous fish were considered to be in "good" condition on the RLS. Reefs with less than 1920 g per 100-m^{-2} herbivorous fish biomass are unlikely to have the seaweeds removed at a fast enough rate to keep the seaweeds from overtaking all the space and driving overall reef health down to a "poor" condition. Herbivorous fish biomass levels of 920 g per 100-m^{-2} or less are ranked as Critical in the RLS.

We only considered herbivorous fishes belonging to the Parrotfish and Surgeonfish family groups in the Herbivorous Fishes category. Some silvery fishes, such as Bream, Chub and Pin Fish also consume marine plants, and are included in the Herbivorous Fishes category in the Bermuda Reef Watch project, but were not included in this report. Additionally, several species of damselfish are herbivores but can have a detrimental effect on reefs, so were also omitted from the Sea Life Index. Plant-eating invertebrates, such as sea urchins, gastropods and hermit crabs were also omitted from the herbivore category.

Table 7. A list of the parrotfishes and surgeonfishes within the Herbivorous Fishes category.

Midnight Parrotfish	*Scarus coelestinus*
Blue Parrotfish	*Scarus coeruleus*
Rainbow Parrotfish	*Scarus guacamaia*
Striped Parrotfish	*Scarus iseri*
Princess Parrotfish	*Scarus taeniopterus*
Queen Parrotfish	*Scarus vetula*
Greenblotch Parrotfish	*Sparisoma atomarium*
Redband Parrotfish	*Sparisoma aurofrenatum*
Redtail Parrotfish	*Sparisoma chrysopterum*
Bucktooth Parrotfish	*Sparisoma radians*
Yellowtail (Redfin) Parrotfish	*Sparisoma rubripinne*
Stoplight Parrotfish	*Sparisoma viride*
Ocean Surgeonfish	*Acanthurus bahianus*
Doctorfish	*Acanthurus chirurgus*
Blue Tang	*Acanthurus coeruleus*

Parrotfishes have been protected species in Bermuda, under the Bermuda Fisheries Act (1972) since 1990, but surgeonfishes remain unprotected. However, surgeonfishes are not target species for either recreational or commercial fishers at this time. Reefs may vary in the biomass of herbivorous fishes due to factors that affect larval fish settlement, habitat availability, water quality, food availability and predator abundance (Tolimieri 1998, Mumby et al 2006, Nemeth and Appeldorn 2009). Management action that enforces the ban on the take of parrotfishes, or which affects water quality and algal abundance, may affect herbivore abundance in Bermuda. Monitoring of surgeonfishes and enhanced fisheries enforcement may be necessary to ensure that these unprotected fishes do not become the targets of new fisher activity..

Predatory Fishes

Predatory fishes are those that eat other fishes. The Predatory Fish Reef Life Score is calculated from the average biomass (g) per 100-m^2 site of one large predator fish: black grouper, and a suite of mid-sized predators: red hind, rock hind, coney, graysby, gray snapper, schoolmaster, lane and yellowtail snapper. Other large grouper species were technically included in the assessment but none were observed on any AGRRA transect across the platform. Jacks and other large predatory fishes including sharks were excluded from the survey as they were not included in the survey methodology developed by McField et al (2007).

The snappers and mid-sized groupers are especially important as they eat damselfish (Steneck and Sala 2005, Vermeij et al 2015), which are small fish that kill hard corals through persistent coral consumption (Kaufman 1977). Large groupers are also important as they feed on smaller parrotfishes, an activity which promotes the abundance of the larger parrotfish species that have a more beneficial impact on reef condition (Mumby et al 2006).

Predatory fishes are the target of both commercial and recreational fishing in Bermuda (Butler et al 1993; Govt. of Bermuda 2014). Most groupers are protected species with no catch allowed, with the exception of Black Grouper and Yellowmouth (Monkey) Rockfish. The Black Grouper are managed through protection of spawning aggregations, and both Yellowmouth Rockfish and Black Grouper are protected with minimum size-limits and catch-per-day limits. Red hind are subject to a minimum size limit and catch limits between May 1 and August 31. Lane and yellowtail snapper species are subject to size-limits and lane snapper to catch-per-day limits. If predatory fishes are found to be in low abundance, fisheries activities needs to be addressed through changes in resource management action, enforcement or legislation.

Table 8. A list of the grouper and snapper species assessed, within the Predatory Fishes category. Other grouper species exist in Bermuda, but none were seen in our surveys.

Black Grouper	*Mycteroperca bonaci*
Graysby	*Cephalopholis cruentata*
Coney	*Cephalopholis fulva*
Rock Hind	*Epinephelus adscensionis*
Red Hind	*Epinephelus guttatus*
Gray Snapper	*Lutjanus griseus*
Lane Snapper	*Lutjanus synagris*
Schoolmaster Snapper	*Lutjanus apodus*
Yellowtail Snapper	*Ocyurus chrysurus*

Sea Life Index

Sea Life Index of each site is calculated by averaging the four component Reef Life Scores of each site. As the values of the SLI for each site are derived from the averages of the RLS, the range of values that define each reef condition level (i.e. Very Good, Poor) do not match those of the components Reef Life Scores. The range of values for each ranking are displayed below:

Table 9. The range of values of the Sea Life Index that correspond to each level of reef condition.

Reef Condition	Critical	Poor	Fair	Good	Very Good
Sea Life Index Score	1.00 to 1.79	1.80 to 2.59	2.60 to 3.39	3.40 to 4.29	4.30 to 5.00

Results

10-m Depth Zone

Hard Coral

24 sites were surveyed across the platform, with 6 transects assessed at each site, for a total of 144 transects assessed within the 10-m depth zone. A box-plot of the results of the surveys of hard corals at these sites is presented in

Fig. 15. Coral cover ranged from a minimum of 16 percent cover at site 1001, to a maximum of 79 percent coral at site 1009.

Coral cover across the 10 m zone was within the 20-50 percent cover range, with the exception of three sites on the south side of the Bermuda platform which displayed coral cover values in the 40-80 percent cover range. Only a few transects at four sites displayed coral cover below 20 percent.

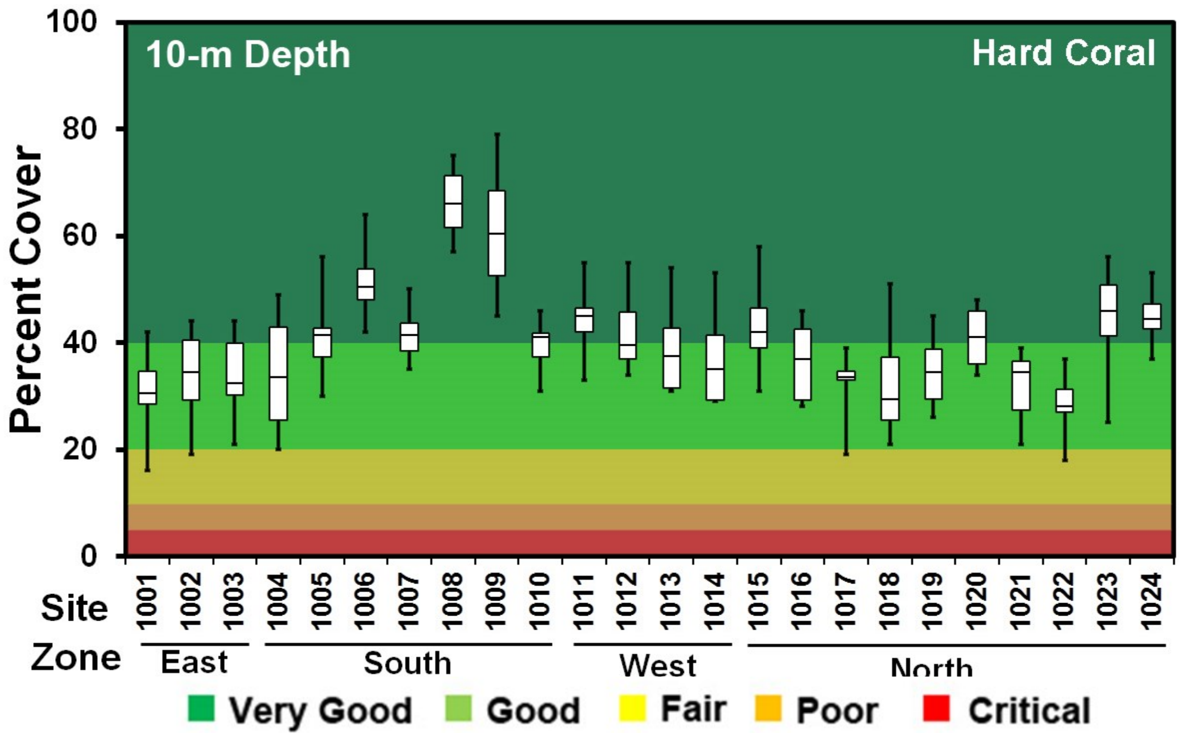

Fig. 15. A boxplot of the percent cover of hard corals across the 24 baseline BREAM sites assessed at 10-m depth in 2010. Average values (centre bar of each boxplot) per site were used to compute the Hard Coral Reef Life Score per site. The range of values of each Reef Life Score is represented in the graph by the five representative coloured zones which match the RLS categories in Table 2.

Fleshy Macroalgae

Fleshy macroalgae was observed across all 24 sites assessed at 10-m depth (Fig. 16). Site 1007 had a zero percent cover of fleshy macroalgae across three transects, while site 1021 displayed up to 49 percent cover. Across the 10-m zone, fleshy macroalgae was generally below 20 percent cover, with only site 1021 displaying high fleshy macroalgae cover in the range of 18-37 percent cover.

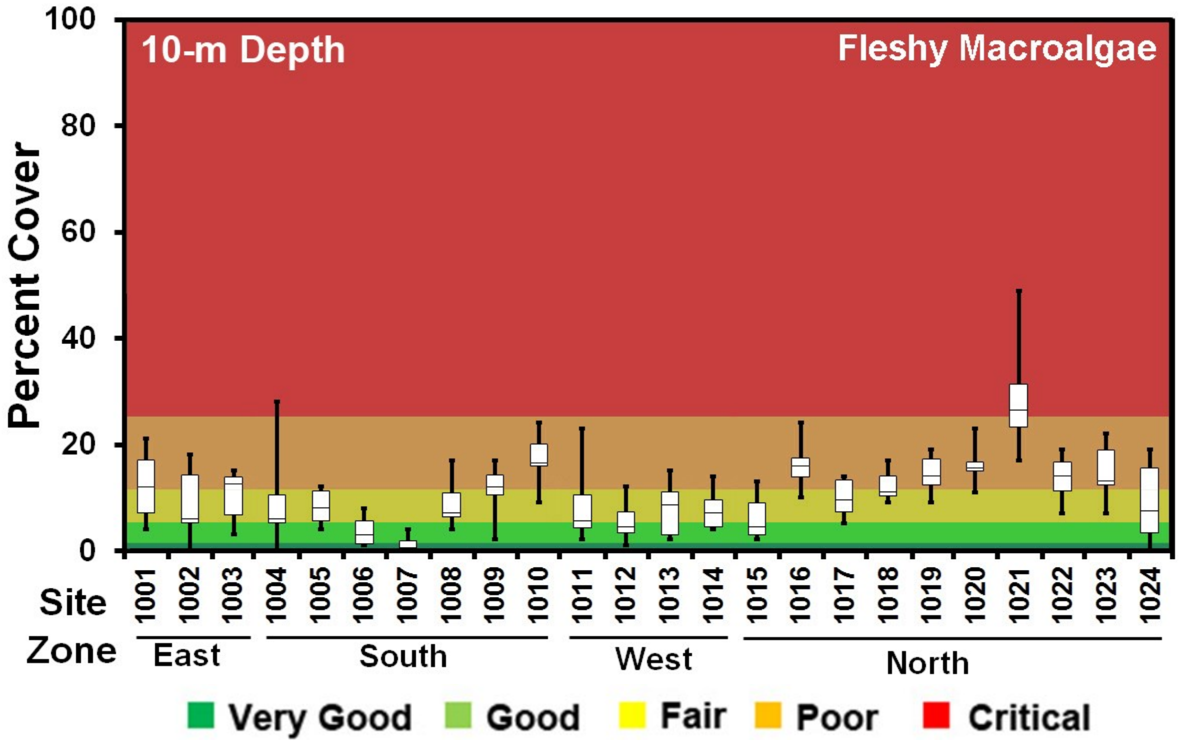

Fig. 16. A boxplot of the percent cover of fleshy macroalgae across the 24 baseline BREAM sites assessed at 10-m depth using the AGRRA method in 2010. Data represent the average, first and third quartile, minimum and maximum value from linear point intercept counts of fleshy macroalgae at 10-cm intervals on six replicate transects measuring 10-m long.

Herbivorous fishes

The herbivorous parrotfishes and surgeonfishes displayed a broad range of biomass levels across both the site scale and the regional scale (Fig. 17). The 10-m site with the greatest biomass of herbivorous fishes was also the site with the greatest range between transects. Site 1007, on the South side of the platform, displayed only 272 g of herbivorous fishes per 100 m^2 at one transect while also displaying 13,297 g per 100 m^2 within another transect. All sectors of the platform at 10-m were observed to support sites with high biomass and sites with low biomass, with no large-scale pattern in parrotfishes being apparent. Generally, the majority of sites were in the fair or better range, with only five sites exhibiting critically low levels of herbivorous fishes.

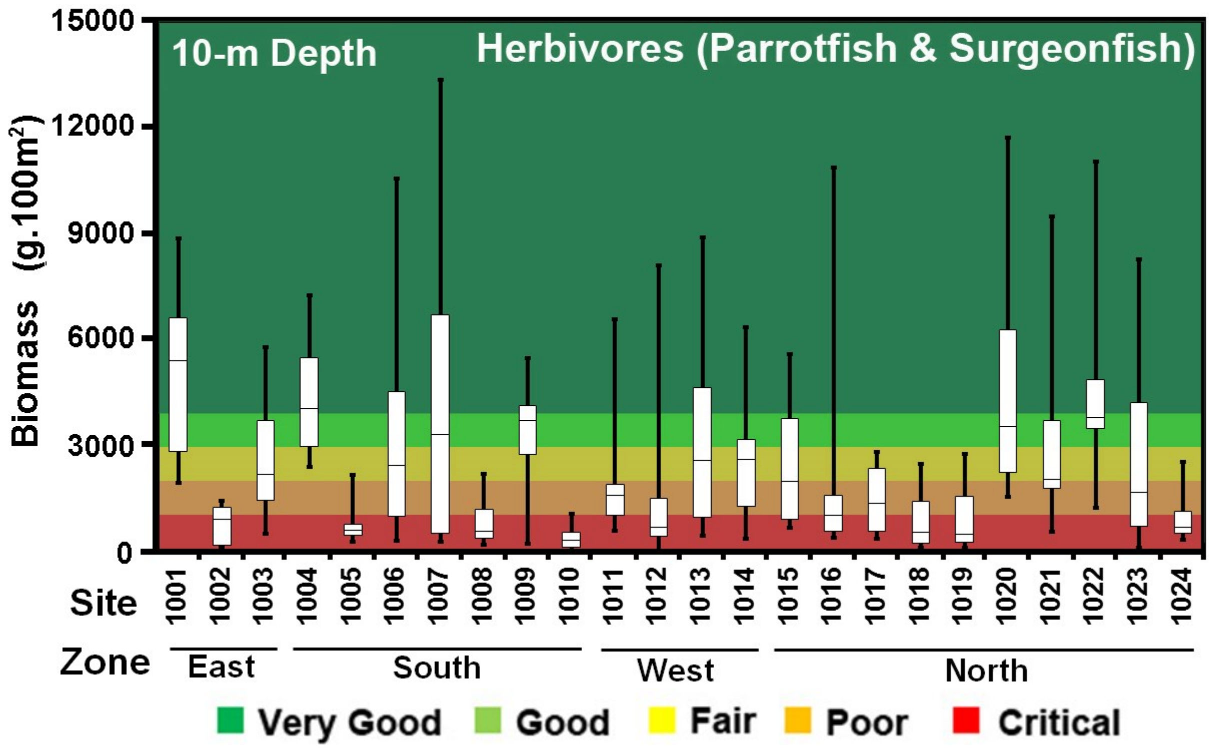

Fig. 17. A boxplot of the biomass of key herbivorous fishes across the 24 baseline BREAM sites assessed at 10-m depth using the AGRRA method in 2010. Data represent the average, first and third quartile, minimum and maximum value from fish counts by size and species along ten replicate transects measuring 30-m long by 2-m wide.

Predatory Fishes

Biomass levels of predatory, or piscivorous, fishes in the snapper and grouper categories were observed to be at critically low or poor levels across the majority of the 10 m sites (Fig. 18). Zero predators were observed on at least one transect at every site across the entire platform at 10-m depth. A maximum of 2,630 g per 100 m^2 observed at one transect, within Site 1023 in the Northern forereef zone.

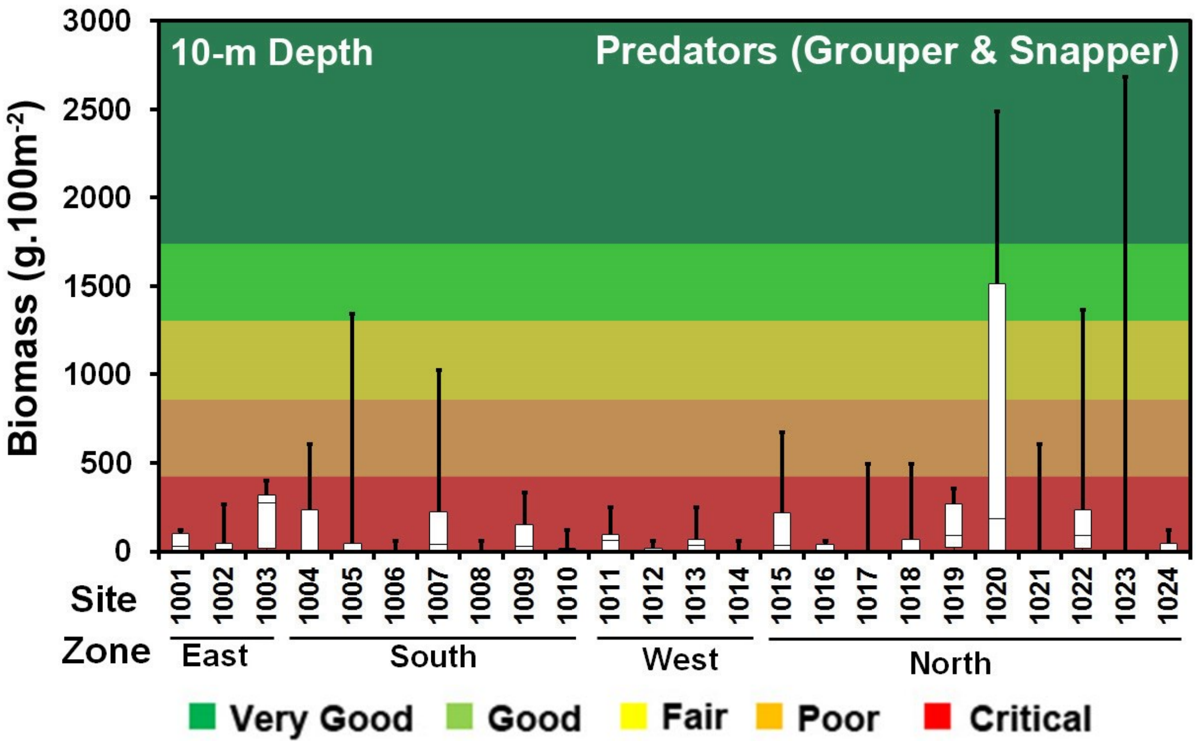

Fig. 18. A boxplot of the biomass of key piscivorous fishes across the 24 baseline BREAM sites assessed at 10-m depth using the AGRRA method in 2010. Data represent the average, first and third quartile, minimum and maximum value from fish counts by size and species along ten replicate transects measuring 30-m long by 2-m wide. Note the y-axis differs from Figure 3.

Sea Life Index

The map in Fig. 19 displays the component RLS and overall SLI score for each site in a spatial manner, with each section of the pie representing RLS for each of the four ecological parameters and the central value the overall SLI score for that site. Table 10 shows the same information in tabular form, which better shows the overall state of each ecological parameter RLS and their contribution to the SLI score.

Sites 1010 and 1018 had the lowest SLI scores, at 2.0 or Poor. Site 1020, seaward of the Snakepit BMPA, had the highest SLI, at 4.3. Generally, the East and West sides of the platform had SLI in the Fair range, while reefs on the South and North sides of the platform also displayed sites in the Good and Very Good grade. As can be seen clearly in Table 10, reef health across the zone was suppressed primarily due to the extensive and critically low levels of predatory fishes observed across the entire 10-m forereef zone. Otherwise, coral cover and herbivorous fishes were generally at healthy high levels and fleshy macroalgae was at a relatively healthy low level across the region.

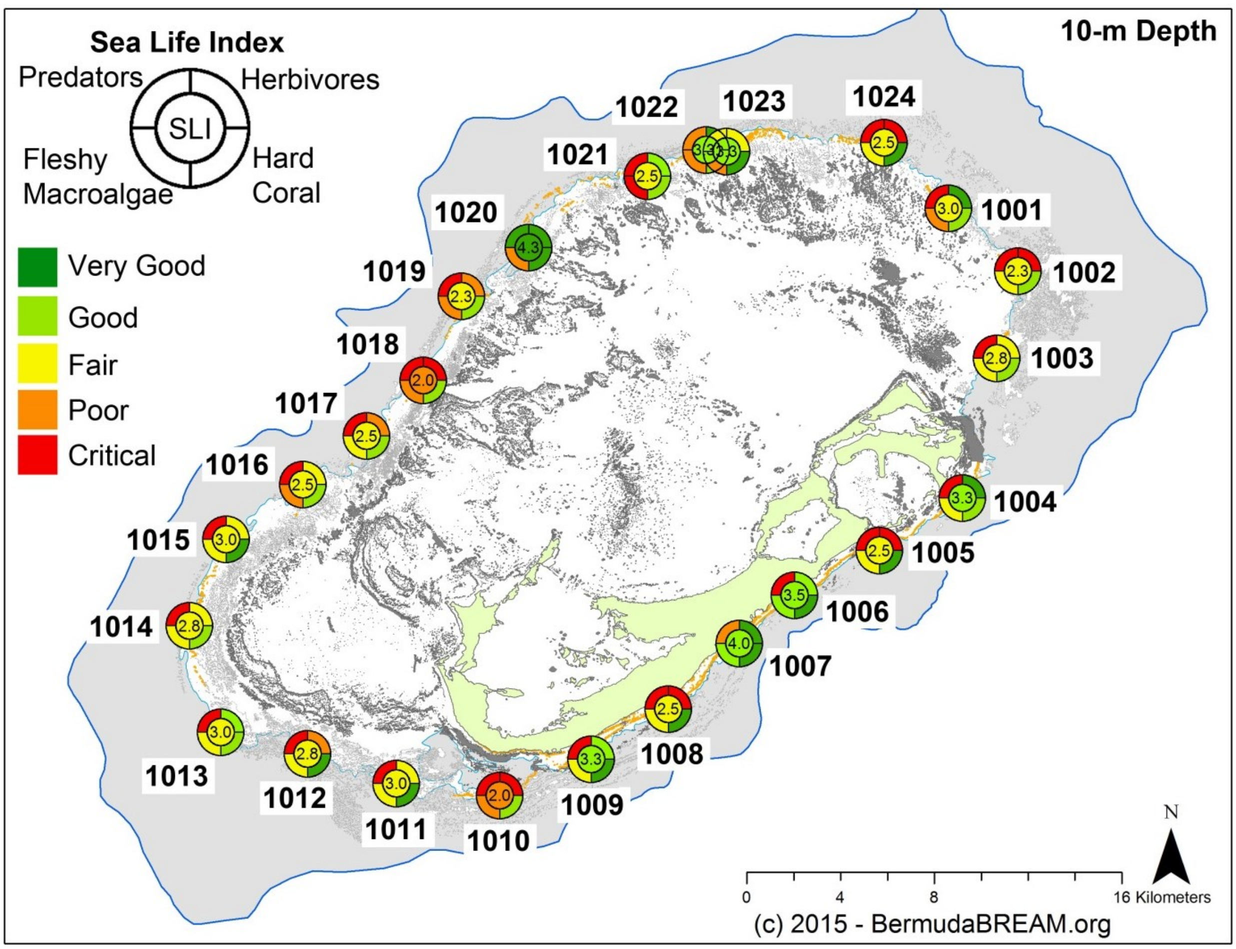

Fig. 19. The Sea Life Index and component Reef Life Scores for each of the BREAM sites surveyed at 10-m depth, illustrating the broad-scale patterns in reef condition relative to position on the reef platform.

Table 10. Reef Life Scores per site across the 10-m depth zone for hard corals (HC), fleshy macroalgae (FMA), herbivorous fishes (HF) and predatory fishes (PF). Reef Life Scores for each category were averaged to generate the Sea Life Index for each reef site across the zone.

Site	HC	FMA	HF	PF	SLI
1001	4	2	5	1	3.0
1002	4	3	1	1	2.3
1003	4	3	3	1	2.8
1004	4	3	5	1	3.3
1005	5	3	1	1	2.5
1006	5	4	4	1	3.5
1007	5	4	5	2	4.0
1008	5	3	1	1	2.5
1009	5	3	4	1	3.3
1010	4	2	1	1	2.0
1011	5	3	3	1	3.0
1012	5	3	2	1	2.8
1013	4	3	4	1	3.0
1014	4	3	3	1	2.8
1015	5	3	3	1	3.0
1016	4	2	3	1	2.5
1017	4	3	2	1	2.5
1018	4	2	1	1	2.0
1019	4	2	2	1	2.3
1020	5	2	5	5	4.3
1021	4	1	4	1	2.5
1022	4	2	5	2	3.3
1023	5	2	3	3	3.3
1024	5	3	1	1	2.5

20-m Depth Zone

Hard Corals

Nineteen sites were surveyed at 20-m depth across the Bermuda forereef. The cover of hard corals varied across the 19 sites (Fig. 20), with a minimum of 16 percent cover on a transect at site 2015, and a maximum of 75 percent cover at site 2008. Generally, the South and West sectors exhibited more hard coral cover, when compared to the East and North sectors, but each sector exhibited a wide range of values. Across the 20-m depth zone, all sites were observed to be in good to very good condition in terms of hard coral cover.

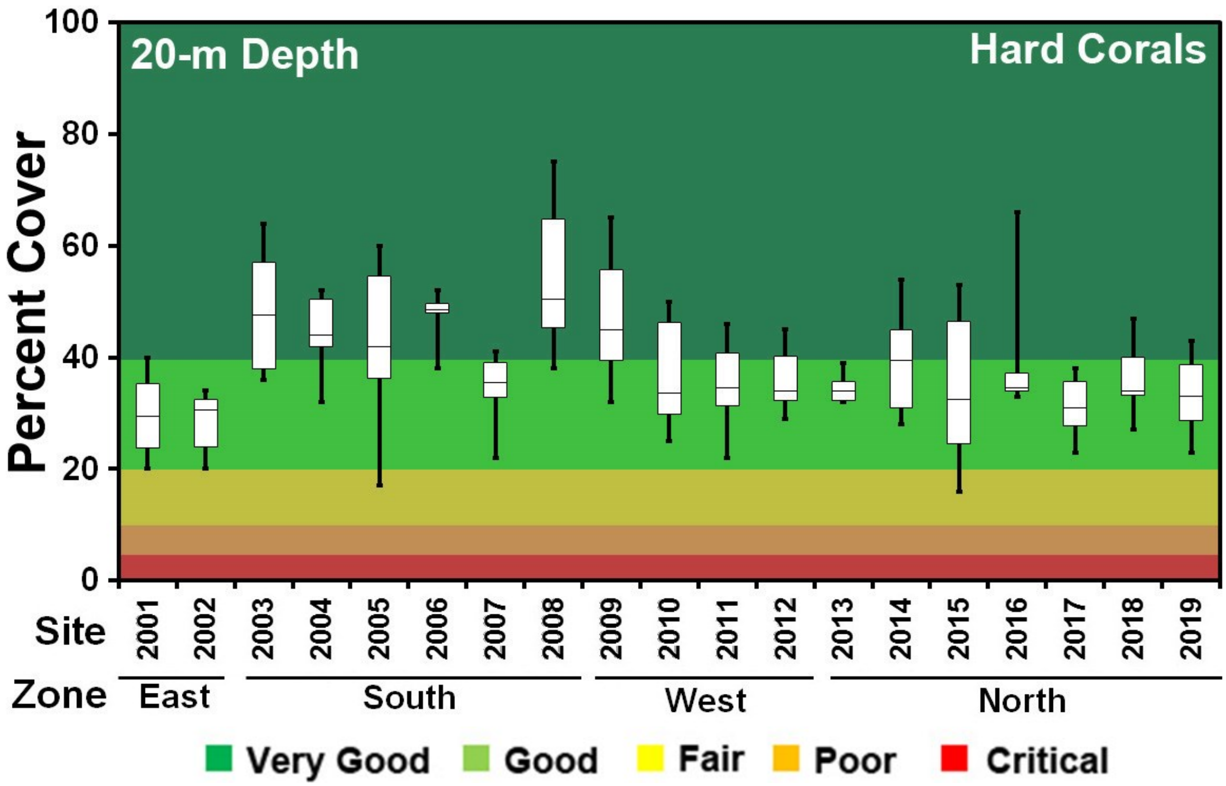

Fig. 20. Boxplots of the percent cover of hard coral from six transects at each sites, assessed in each of 19 sites surveyed around the Reef Platform in the 20-m depth zone.

Fleshy Macroalgae

Fleshy marine plants ranged across transects and sites from a high of 42 percent cover at site 2009, to zero cover at many sites across the zone (Fig. 21). Overall, fleshy macroalgae was observed to be at a healthy low abundance across most of the East and South sectors, but at higher, less healthy levels of coverage across the West and North sectors. Only site 2019, in the North sector, displayed critically high levels of fleshy macroalgae cover across the 20-m depth zone.

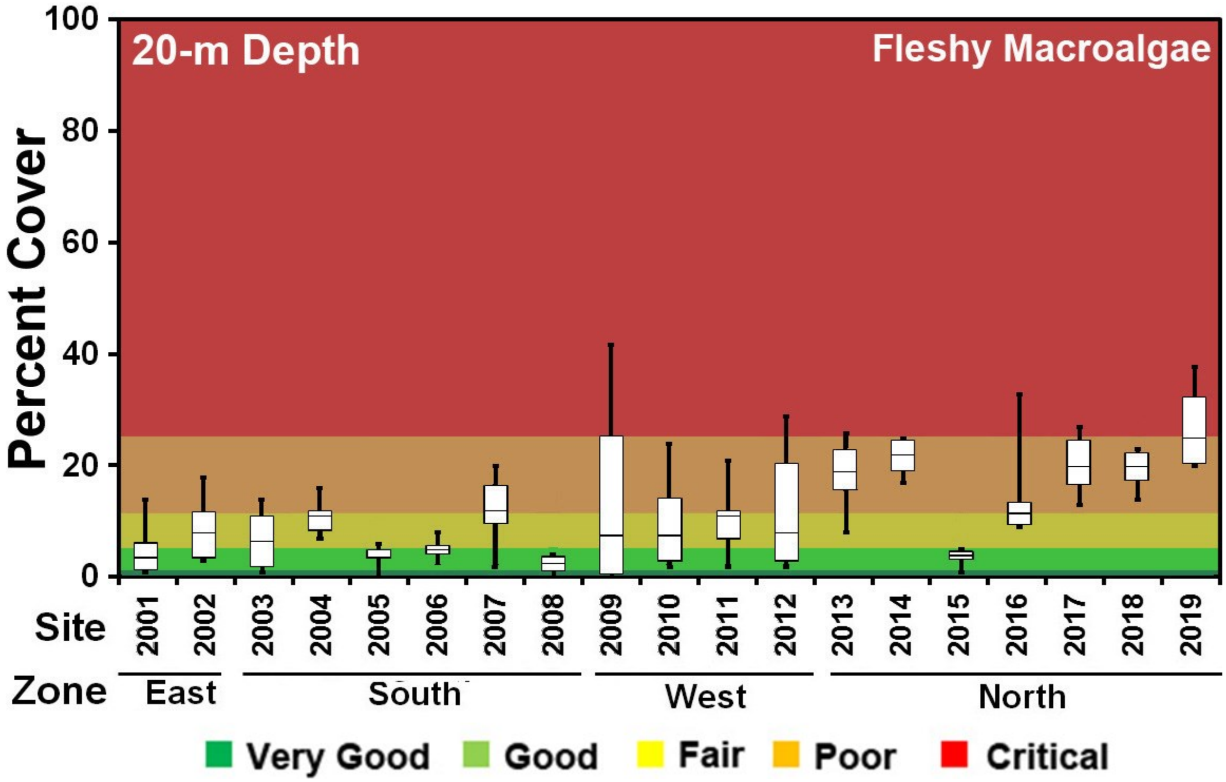

Fig. 21. Boxplot of the percent cover of fleshy macroalgae assessed in six transects at each site, across the 19 sites surveyed at 20-m depth around the Bermuda reef platform.

Herbivorous Fishes

The plant-eating parrotfishes and surgeonfishes displayed critically low levels of biomass across the entire 20-m zone thoughout all four sectors (Fig. 22). The highest biomass of herbivores were observed in the East sector at site 2001, 2002 and in the North sector at site 2013. The south sector in particular displayed very low levels of herbivorous fish biomass.

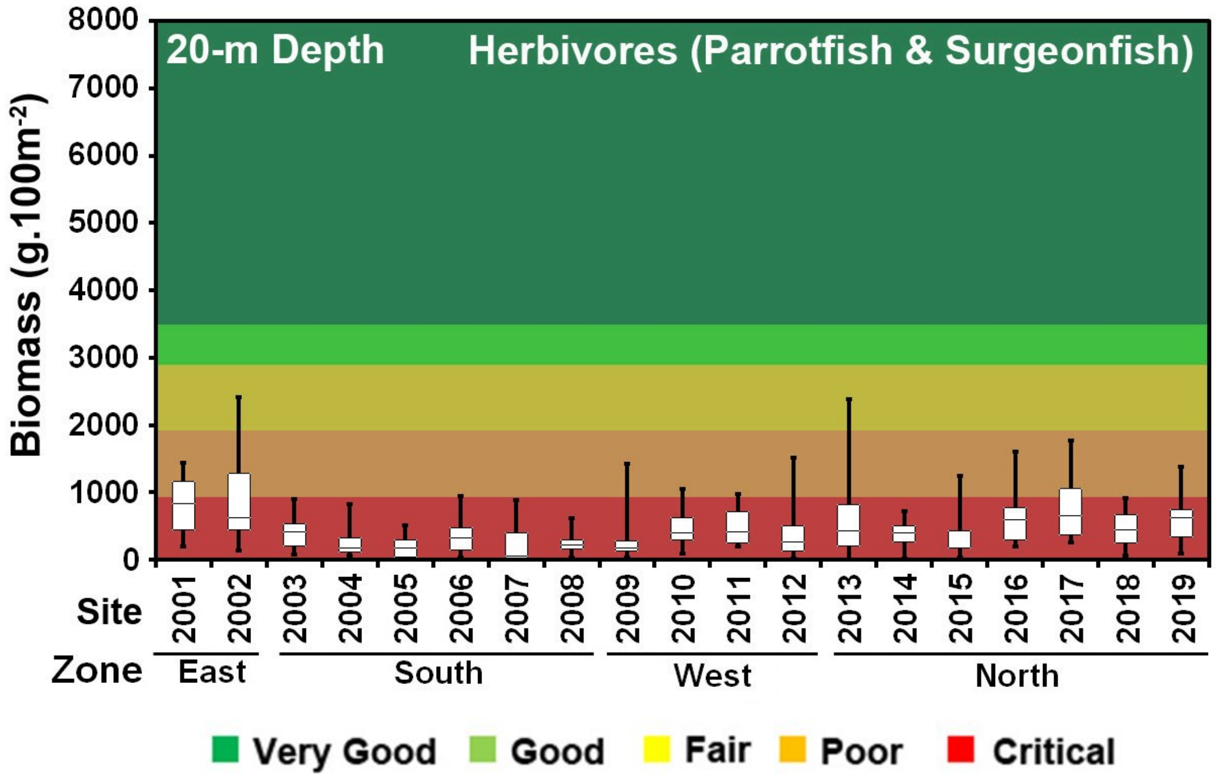

Fig. 22. Biomass of herbivorous fishes on ten transects across the 19 sites surveyed at 20-m depth. Colours indicate how biomass levels corrrespond with SIHRI catagories of ecological health. Higher biomass levels of herbivores represents better levels of ecological condition.

Predatory Fishes

Predatory fish biomass was critically low across the entire 20-m depth zone at all sites (Fig. 23), with the exception of site 2013 with displayed a high biomass level over 6 kg per 100 m^2 within one tranect out of ten. Across the region the North sector had marginally more predators than the other three sectors, but all sectors were critically depleted in predators. It should be noted, that while we did find low densities of parrotfish and other herbivorous fishes at 20-m depth, unpublished BREAM data shows that another component of the herbivore guild known as "microherbivores", which are small plant-eating snails (*Cerithium spp.*) and hermit crabs (*Calcinus spp.*), are abundant at 20-m depth. It is likely these "micro-herbivores" are responsible for maintaining low levels of marine plants and promote reef condition in a manner not observed using the methods of this study. A follow-up study will expand upon the 4-component SLI to include the micro-herbivores and several other important biological components of reef condition. Additionally, long-term monitoring by BREAM will collect data on the expanded list of indicator parameters.

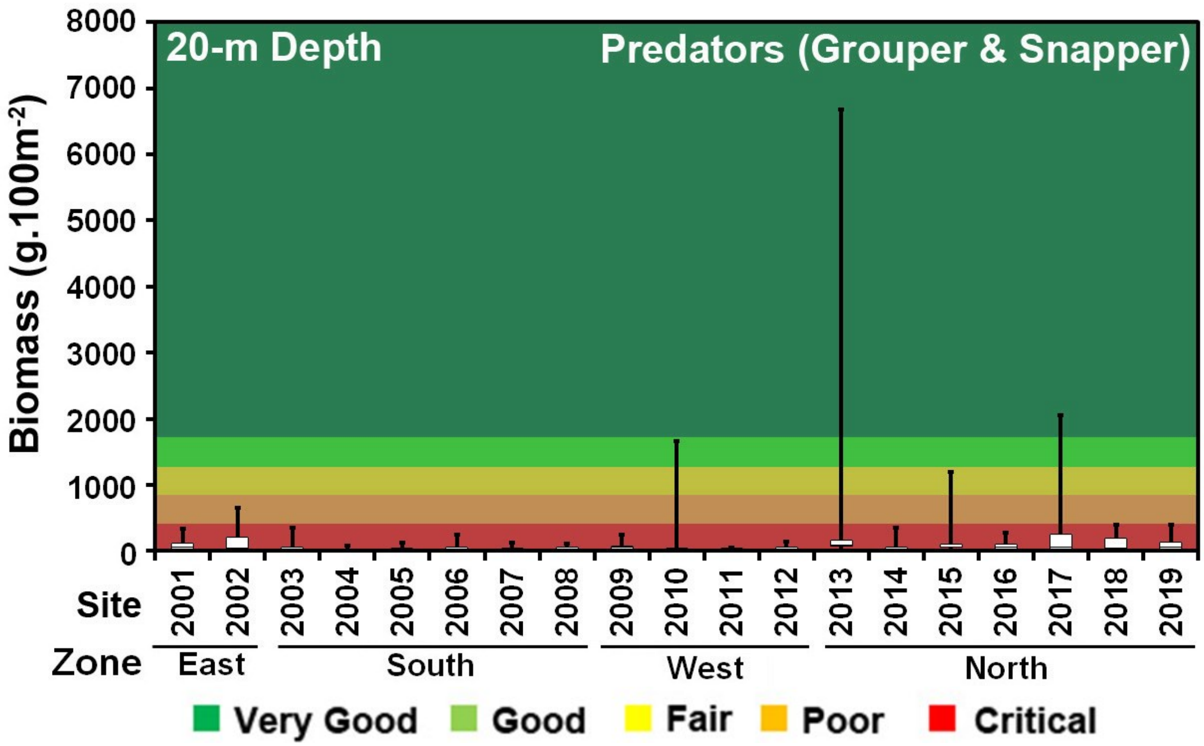

Fig. 23. Boxplots of the biomass of predatory fishes (grouper and snapper) as counted in ten transects across the 19 sites at 20-m depth from around the Bermuda platform.

Sea Life Index

Reef Life Scores were used to calculate SLI for the 19 reef sites assessed across the 20-m depth zone on the forereef of Bermuda. Overall the 19 coral reefs in the 20-m depth zone were found to be in either poor or fair condition (Fig. 26: Table 11). Sites 2017 – 2019 were the largest cluster of sites with comparably poor SLI scores in the 1.8 to 2.0 range (Poor). Very low amounts of herbivore and predatory biomass were the primary reason for the low overall health scores across the 20-m forereef zone. High coverage of fleshy macroalgae also contributing to the poorest sites. As can be seen in Table 11, the hard coral cover of the reefs at 20-m depth were good or very good, contrary to the unfavourable levels of the other three reef health indicators.

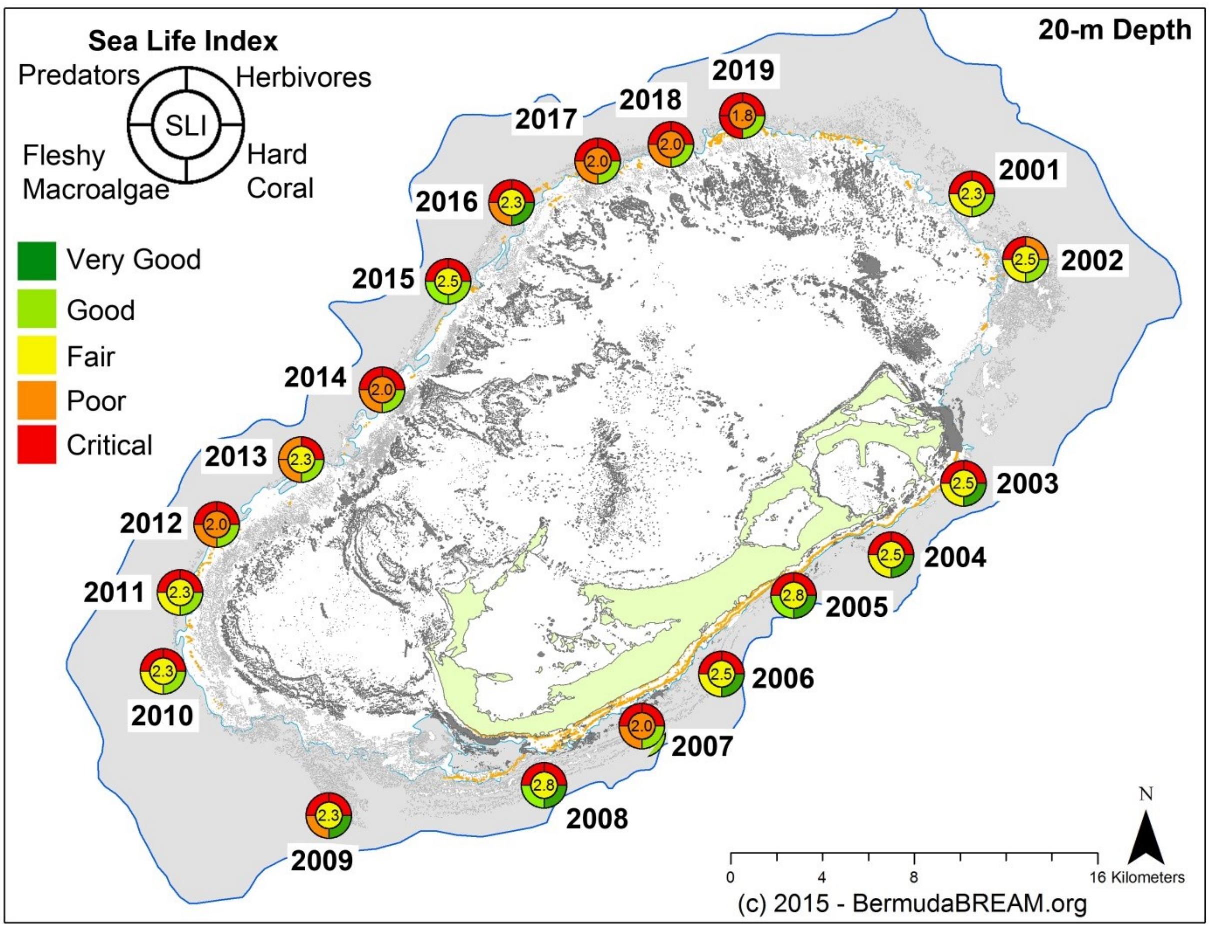

Fig. 24. The Reef Life Score for each biotic component and the overall Sea Life Index value for each site surveyed at 20-m depth, displayed in a spatially representative manner.

Table 11. The Sea Life Index (SLI) values and component RLS for the 19 reefs surveyed at 20-m depth. HC: Hard Coral, FMA: Fleshy Macroalgae, HF: Herbivorous Fishes; and PF: Predatory Fishes.

20 m	HC	FMA	HF	PF	SLI
2001	4	3	1	1	2.3
2002	4	3	2	1	2.5
2003	5	3	1	1	2.5
2004	5	3	1	1	2.5
2005	5	4	1	1	2.8
2006	5	3	1	1	2.5
2007	4	2	1	1	2.0
2008	5	4	1	1	2.8
2009	5	2	1	1	2.3
2010	4	3	1	1	2.3
2011	4	3	1	1	2.3
2012	4	2	1	1	2.0
2013	4	2	1	2	2.3
2014	4	2	1	1	2.0
2015	4	4	1	1	2.5
2016	5	2	1	1	2.3
2017	4	2	1	1	2.0
2018	4	2	1	1	2.0
2019	4	1	1	1	1.8

30-m Depth Zone

Hard Corals

The percent cover of hard corals across 24 reef sites at 30m depth was assessed by video drop camera (Fig. 25), as varying high numbers of video quadrats from single video transects per site. Box-plots in this depth zone represent variability in hard coral cover across video frames taken from a single 350-500 m long transect taken at each site, not transects within sites, and therefore the data from site to site exhibits a much broader range of values compared to the plots from the 10-m and 20-m analyses of coral cover. Coral cover ranged across sites with a maximum value of ~60 % in a frame at site 3013. Median coral cover was fair to poor overall, with sites 3004 and 3001 possessing poor to critically low levels of hard coral cover. In general, the West and North sites at 30-m depth (e.g. 2013 and 2014) displayed more hard coral cover than did the reefs in the East and South sectors

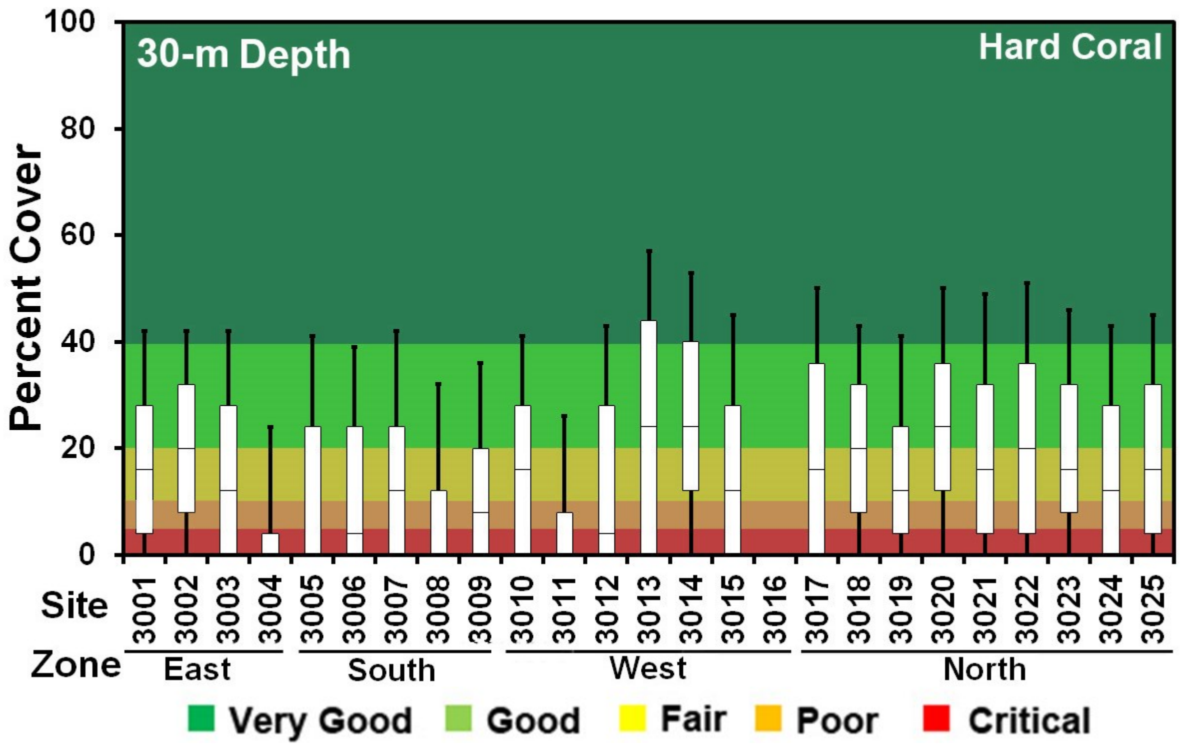

Fig. 25. Box-plots of the percent cover of hard corals per frame from single video transects at each site at 30-m depth, as filmed by high-definiton video drop-camera.

Fleshy Macroalgae

Fleshy marine plants covered a moderate to high proportion of the the available space at the majority of 30-m deep sites surveyed by drop camera (Fig. 26), and almost all sites ranked as "critical". Overall fleshy macroalgae abundance was higher in southern and northern sites relative to eastern and western sites.

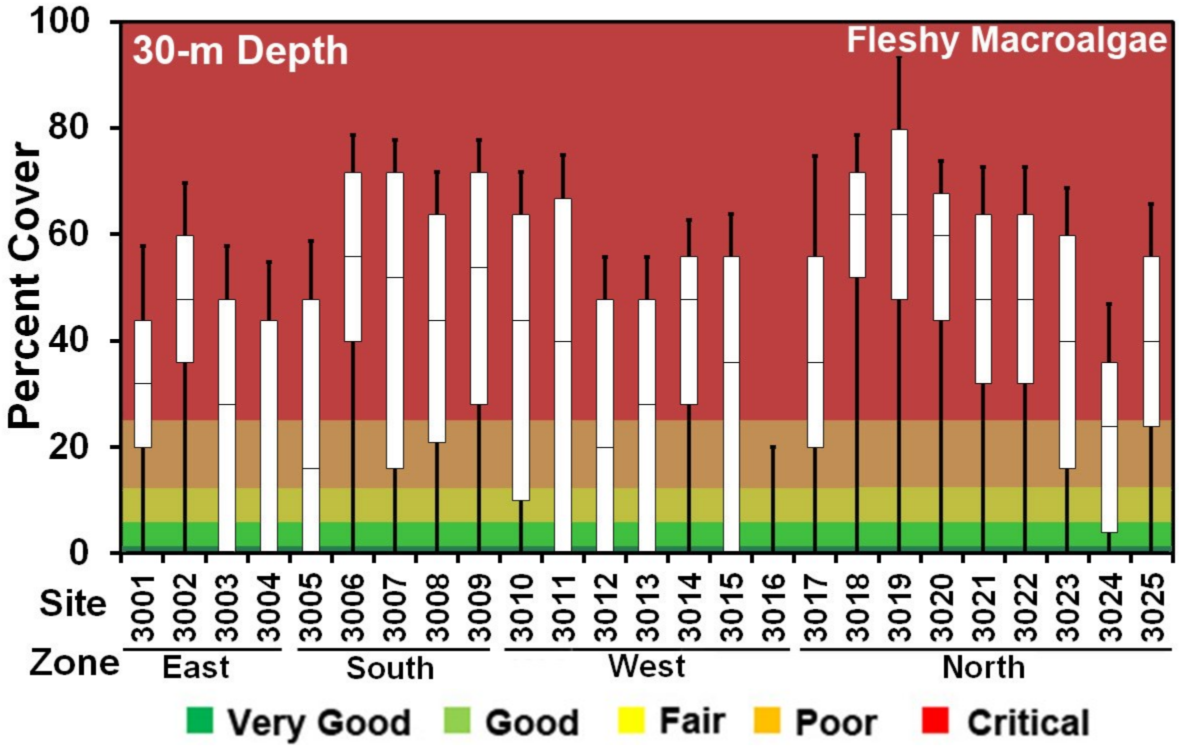

Fig. 26. Boxplot of the percent cover of fleshy macroalgae and *Lobophora* sp. as assessed in individual frames of individual video transects measuring 350-500 m in length at each site.

Herbivorous Fishes

Plant-eating fishes in the parrotfish and surgeonfish families only displayed high biomass at one site at 30-m depth (Fig. 27). The majority of sites in the southern and western sectors were found to have critically low biomass in the herbivorous fishes. The north sector had poor levels of biomass in most sites, with fair biomass only at the eastern end of the northern sector (i.e. Sites 3001, 3023 – 3025)

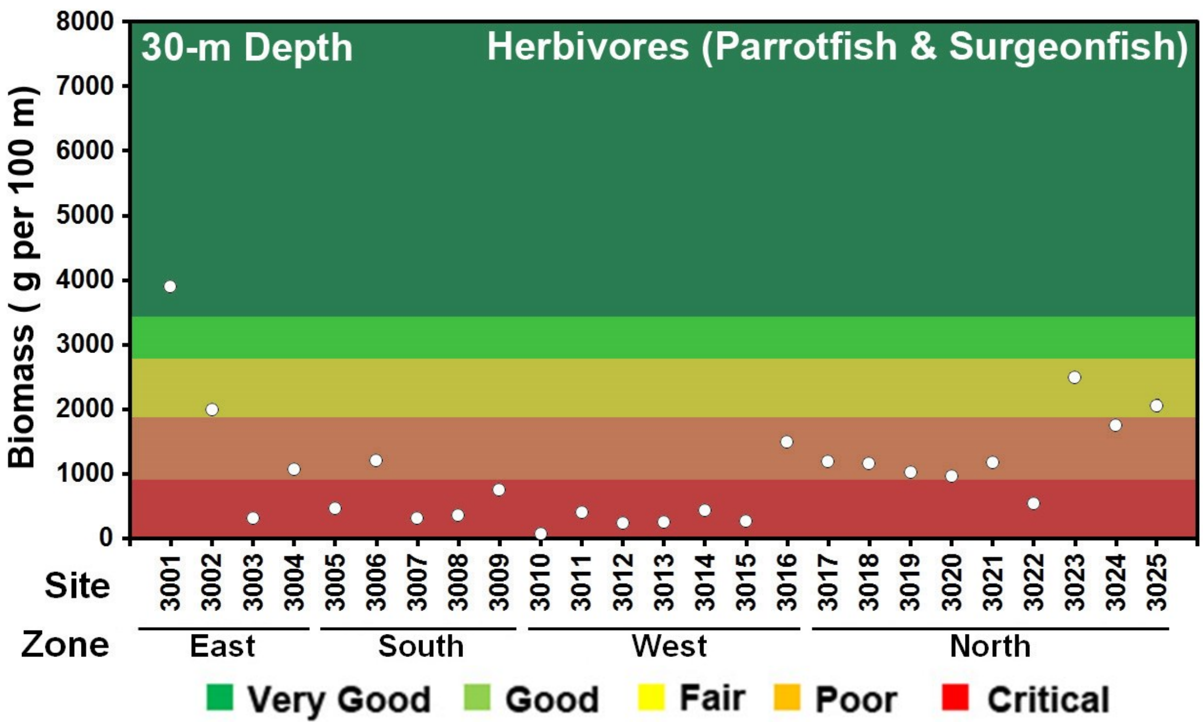

Fig. 27. Each point represents total biomass of plant-eating parrotfish and surgeonfish at the 24 sites assessed by drop camera at 30-m depth. Biomass was calculated from total counts of fish in each 350- to 500-m long transect sorted by estimated size as observed in a forward faced high-definition video camera.

Predatory Fishes

Piscivorous fishes were observed to be critically low abundance at all sites surveyed at 30-m depth (Fig. 28). Most sites throughout all sectors did not display any predatory fishes.

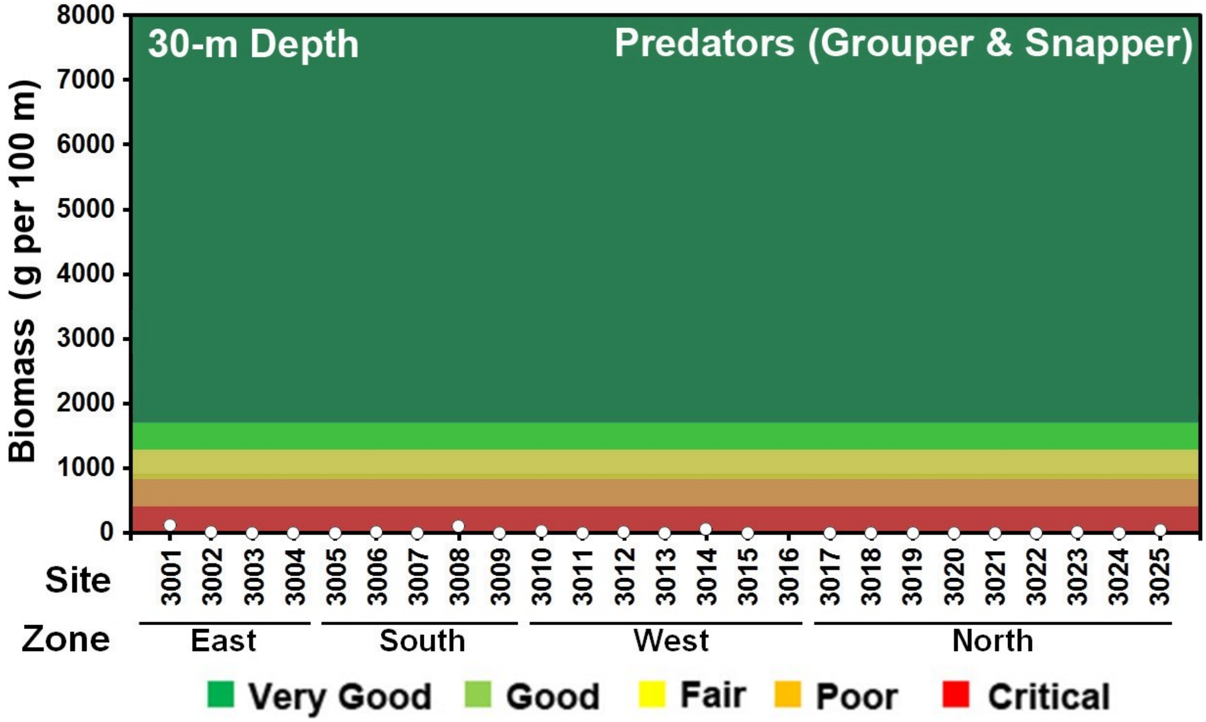

Fig. 28. Total biomass of predatory fish at the 24 sites assessed by drop camera at 30-m depth. Biomass was calculated from total counts of fish sorted by estimated size as observed in a for-ward faced high-definition video camera. N.B. Any biomass below 420 g per 100 m was considered “critical”.

Sea Life Index

The Sea Life Index for the 25 sites surveyed at 30-m depth by drop camera array are mapped in Fig. 29 and presented in Table 12. Very high levels of fleshy macroalgae and very low biomass in predatory fishes across the entire reef zone, and low biomass of herbivorous fishes across the southern and western reef sites, caused the general trend of poor to slightly fair reef health across the 30-m depth zone, regardless of sector. In regards to the broad-scale patterns, the northern and eastern sectors were ranked as fair, while the southern and western sectors were scored as poor. Hard Coral cover was generally fair to good, but Fleshy Macroalgae Cover, Herbivorous Fish and Predatory Fish biomass levels were poor to critical across almost all sites at 30-m depth regardless of which side of the platform the sites were surveyed.

It should be noted that, due to the attenuation of light with depth, the reefs at 30-m depth are exposed to a lower amount of photosynthetically utilizable radiation available to plants and animals on an annual basis, which affects both benthic and fish assemblage structure (Lesser et al 2009). The Sea Life Index was developed for shallow-water reefs. It may be that the same standards for coral fleshy macroalgae, herbivorous and predatory fish do not apply at 30-m depth. Further study is needed before coral reef scientists understand the ecology of deeper coral reef habitat across the entire Caribbean (Kahng et al 2010). Nonetheless, it is also possible that the deeper reefs at 30-m depth function in the same manner as shallow reefs that are exposed to reduced availability to light, due to factors such as high sediment load in the water, or shading from neighbouring landscape features. If this is the case, then it is appropriate to apply the SLI as we have in this report, and the low zone-wide SLI scores appropriately indicate that deeper reefs are naturally in a poorer ecological condition relative to well -lit shallow reefs.

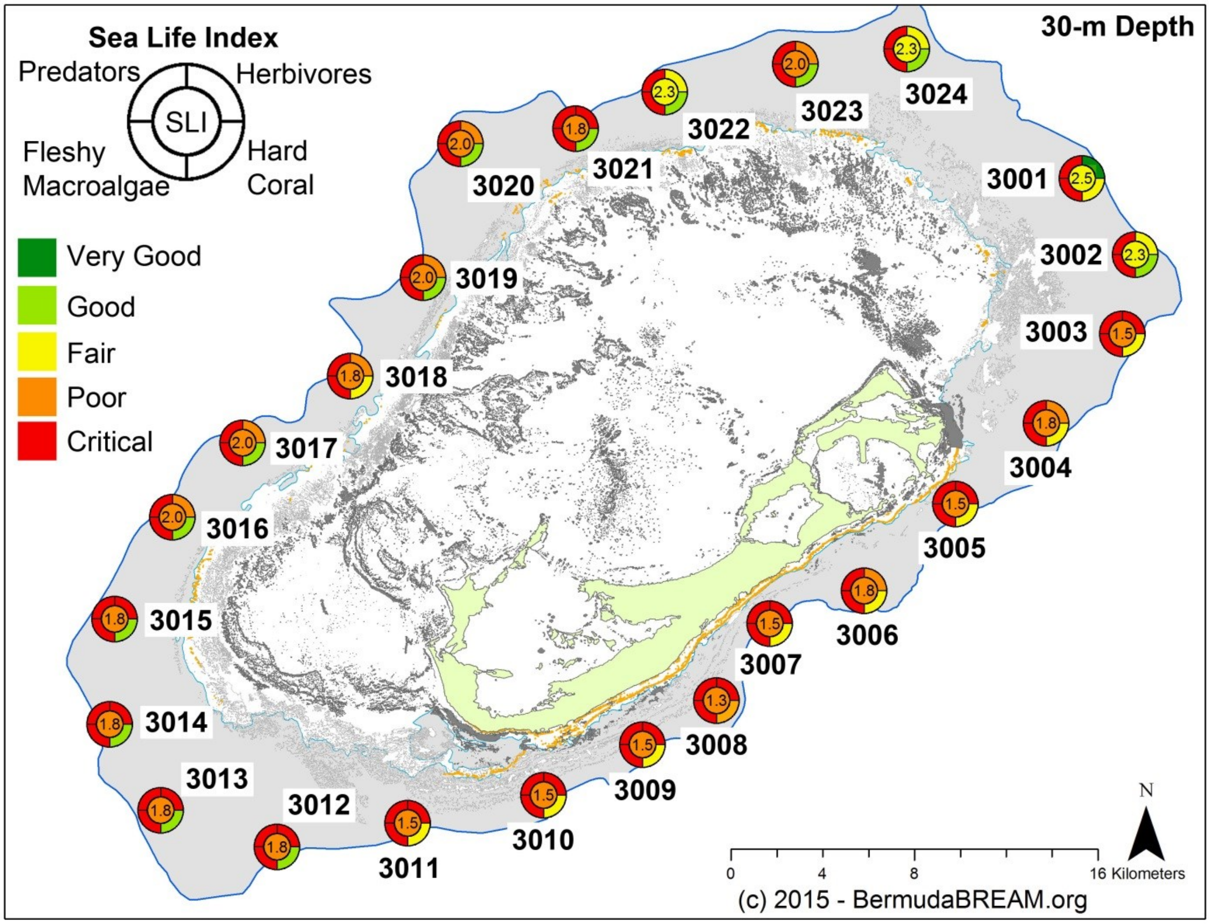

Fig. 29. A spatial representation of the relative condition of reef sites, as indicated by the separate Reef Life Scores, and the computed Sea Life Index.

Table 12. The Reef Life Scores, and Sea Life Index, for the 24 sites assessed at 30-m depth by drop camera. HC: Hard Coral, FMA: Fleshy Macroalgae, HF: Herbivorous Fishes; and PF: Predatory Fishes.

Site	HC	MA	HF	PF	SLI
3001	3	1	5	1	2.5
3002	4	1	3	1	2.3
3003	3	1	1	1	1.5
3004	3	1	2	1	1.8
3005	3	1	1	1	1.5
3006	3	1	2	1	1.8
3007	3	1	1	1	1.5
3008	2	1	1	1	1.3
3009	3	1	1	1	1.5
3010	3	1	1	1	1.5
3011	3	1	1	1	1.5
3012	4	1	1	1	1.8
3013	4	1	1	1	1.8
3014	4	1	1	1	1.8
3015	4	1	1	1	1.8
3017	4	1	2	1	2.0
3018	4	1	2	1	2.0
3019	3	1	2	1	1.8
3020	4	1	2	1	2.0
3021	4	1	2	1	2.0
3022	4	1	1	1	1.8
3023	4	1	3	1	2.3
3024	4	1	2	1	2.0
3025	4	1	3	1	2.3

Platform-wide Comparison of Reef Condition

We generated Reef Life Scores and Sea Life Index values for the other Bermuda reef zones surveyed previously by BREAM (Murdoch et al 2008; Hammond et al 2008), to permit their comparison to the Forereef zones examined in the previous sections. This also allowed us to generate an overall Sea Life Index grade for the whole platform. Fringing reefs (those adjacent to the coastline) and lagoonal Patch reefs were surveyed in 2004 and 2005. Rim reefs were surveyed in 2006. MPA reefs were surveyed in 2009 and 10-, 20- and 30-m reefs were surveyed in 2010-11.

Fringing Reefs

Fringing reefs are located close to land, and are exposed to a broad range of negative environmental and anthropogenic conditions, including a broader range of water temperatures, higher sediment levels and higher exposure to anthropogenic impacts. The fringing reefs at the eastern end of the island were all graded as Poor, while the reefs at the western end of the island were graded as fair to good. It may be that falling tides and the prevailing winds from the Southwest in summer expose the eastern fringing reefs to harmful warm and sediment-laden lagoonal water from the central lagoon, while the same inimical lagoonal water is prevented from reaching the western fringing reefs due to the location of the islands of Sandys Parish.

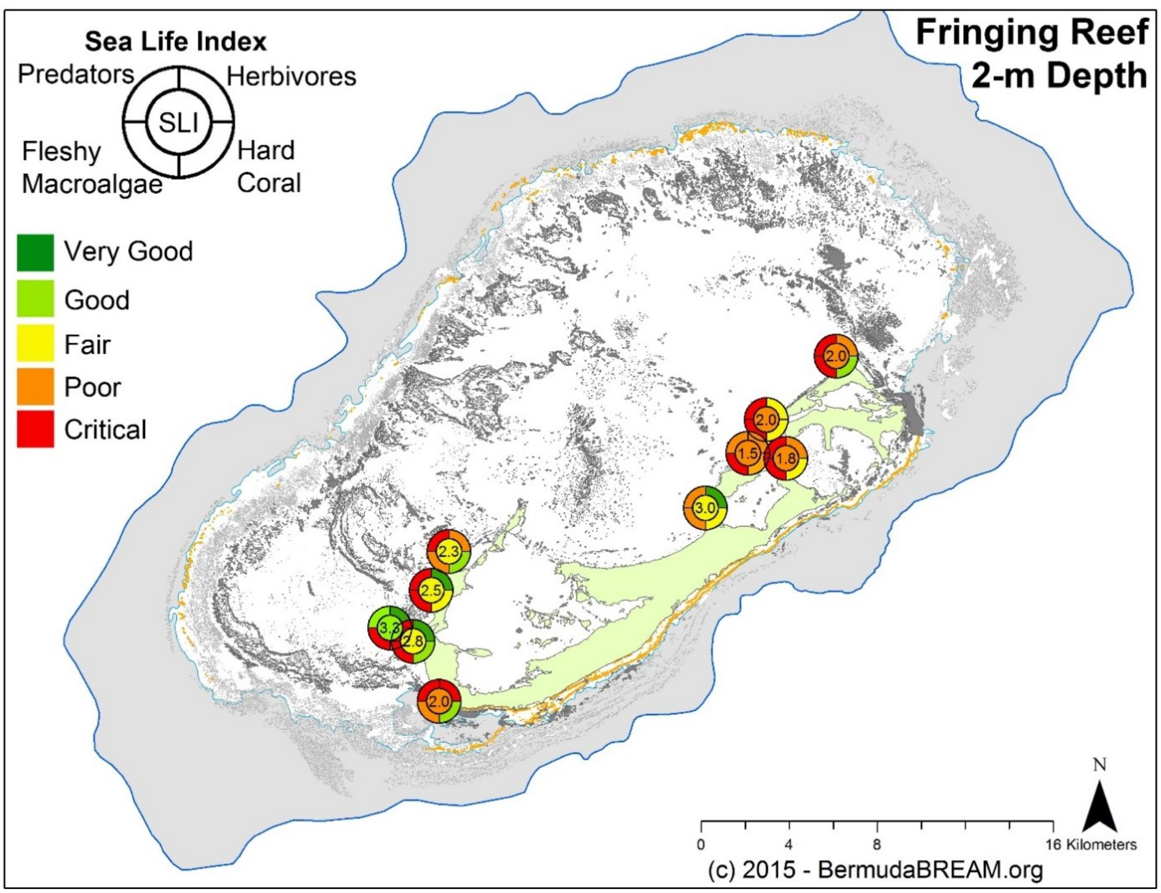

Fig. 30. SLI status for fringing reef sites found along the nearshore of the Bermuda Island.

Lagoonal Patch Reefs

Across the lagoon as in most reef zones, predatory fish are at Critical levels in almost all sites. Predatory fish are only abundant near North Shore and along Three Hill Shoals. Lagoonal patch reefs display both a broad range of SLI values and the highest overall condition, at a site near North Shore and another site near Hog Channel in the Western Lagoon.

The Patch Reef zone is also surveyed using a similar SLI by citizen scientists with the Bermuda Reef Watch project (Murdoch 2014, 2014b, 2015). The SLI scores across sub-lagoonal sectors will be compared to both SLI scores collected by the Bermuda Reef Watch citizen scientists and the BREAM team in their long-term reef resilience monitoring project.

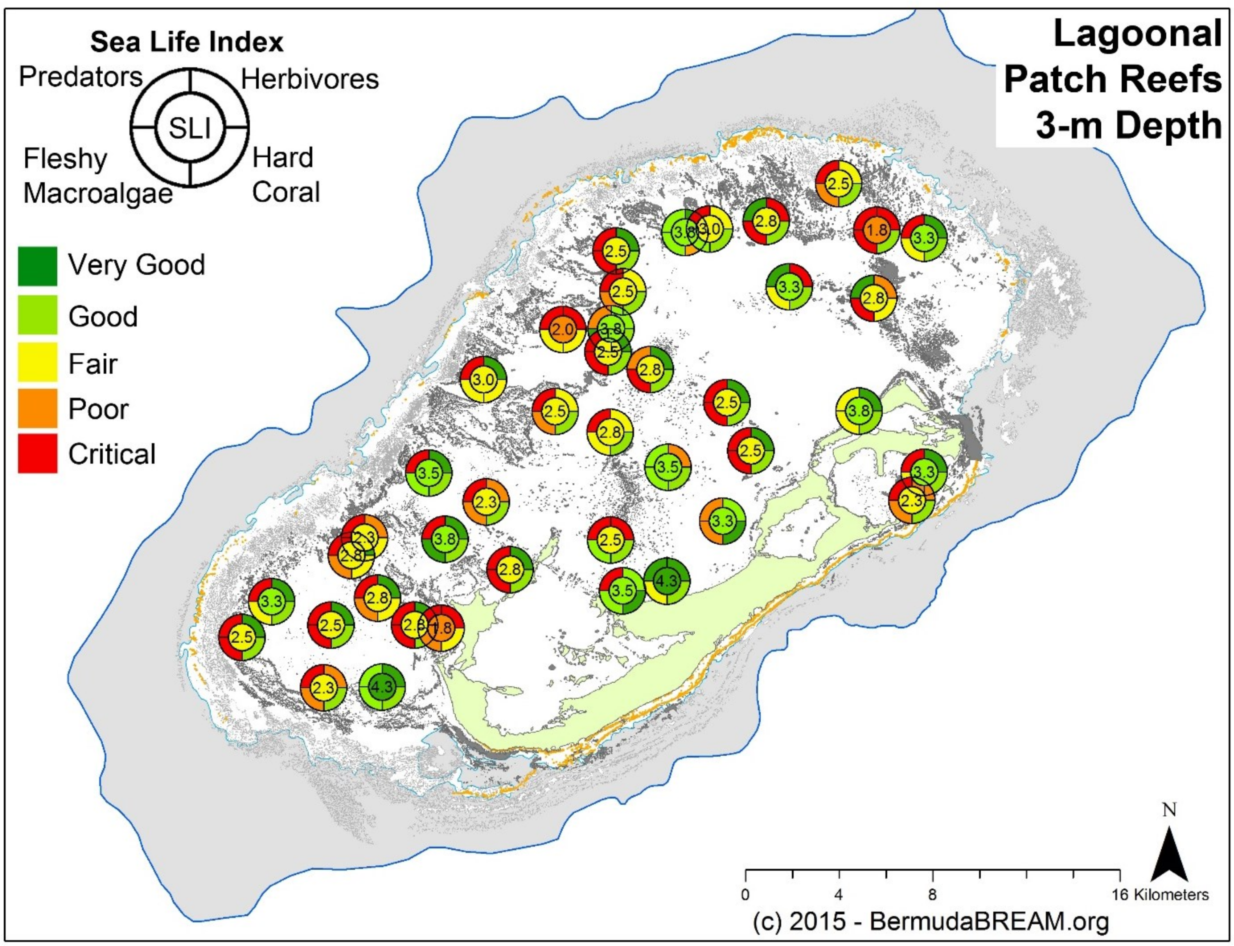

Fig. 31. The SLI status of patch reefs surveyed in 2004 and 2005 by the BREAM team.

Rim Reefs

Rim reefs are located around the entire reef platform at a depth of 2- to 4-m below sea level, and bear the brunt of storm waves. Rim reefs assessed in this report displayed a large variability in overall SLI, with a minimum score of 1.3 on a reef near St. David's, and a maximum score of 4.0 within the buoyed marine protected area at North Rock. Predatory fishes were consistently absent from all but a few rim reef locations. Herbivorous fishes were abundant along the western end of South Shore, at the western extreme of the lagoon (in the area around Chub Cut Beacon), and at the northern extreme of the lagoon (around North Rock). Herbivorous fishes were less abundant in the Western Ledge Flats and the east end of the island. Hard coral cover was generally Good to Very Good across the rim reefs, while macroalgae cover tended to be critical along the South Shore of the island and along the Western Ledge Flats.

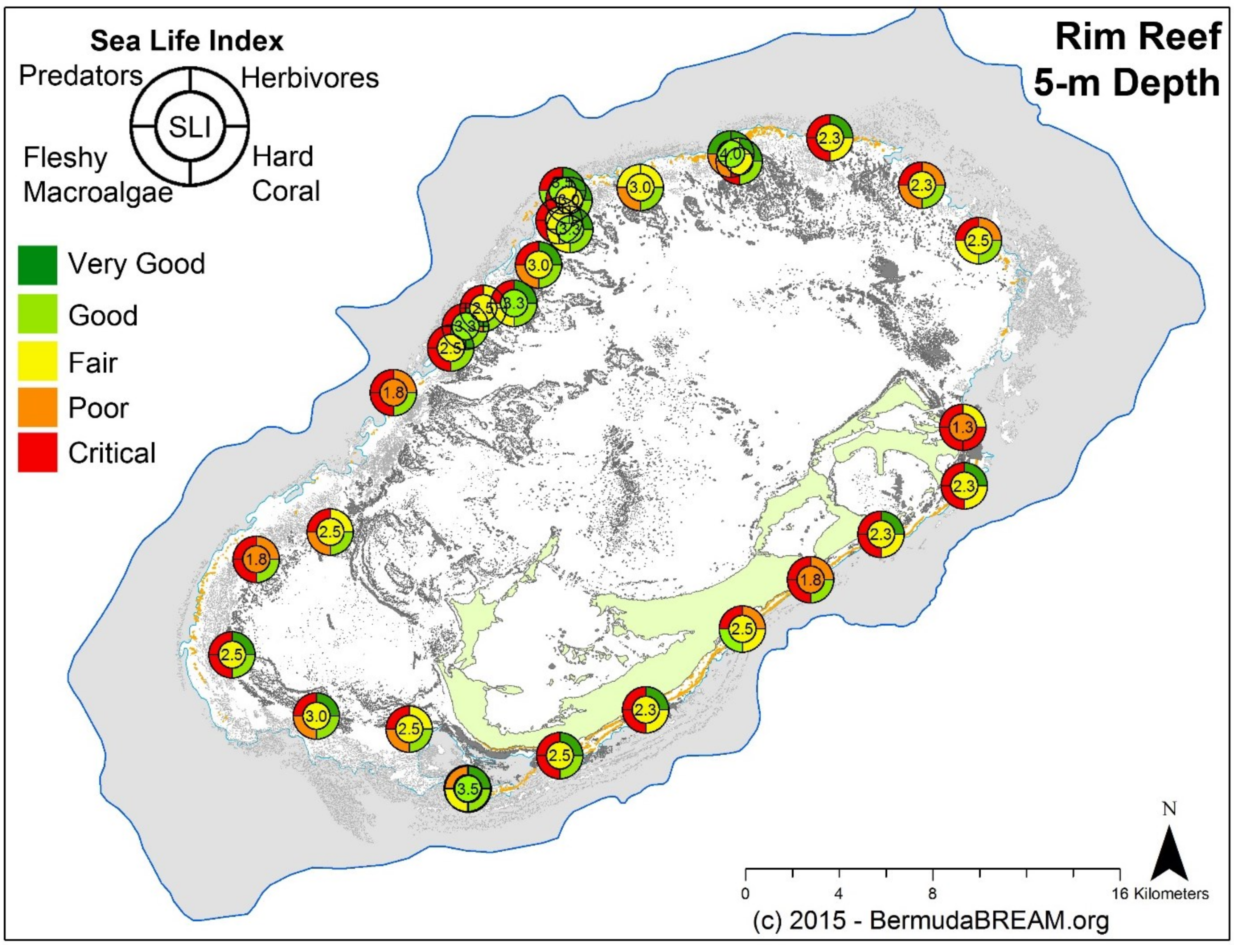

Fig. 32. The Sea Life Index and status of component factors at rim reef sites surveyed between the years 2006 and 2008.

Proportion of Reefs in each Rank of the Reef Life Score

Hard Coral
Generally, the Hard Coral component of the Reef Life Score follows a trend in which hard corals were in very good or good condition at a majority of sites on the 10-m forereef. The Hard Coral component was seen to be in good to fair or poor condition at a greater proportion of sites down the forereef or across the lagoon towards shore. (Fig. 33).

Fleshy Macroalgae
Higher cover of fleshy macroalgae cover indicates reef sites of poorer condition and lower RLS grades. Fleshy Macroalgae demonstrated a more complicated trend than Hard Corals across zones (Fig. 34). Both nearshore fringing reefs and 30-m deep forereefs were dominated by sites with over 50% macroalgae cover. Most other zones displayed a broad range of fleshy macroalgae cover with some reefs having good to very good scores, and some reefs exhibiting poor or fair scores.

Herbivorous Fishes
High levels of fish biomass within a site result in better ratings of Reef Life Score condition in the Herbivorous Fishes category (Fig. 35). Sites with critical and poor scores dominated the 20-m and 30-m forereef, and half of the MPA sites, while reefs with very good RLS dominated the Rim sites, the 10-m depth zone on the forereef, and inside the Patch and Fringing zones of the lagoon.

Predatory Fishes
Predatory fishes such as large and small grouper, and snappers, contribute positively to reef condition, and reefs with high levels of biomass have a more positive condition index. Fig. 36, however, demonstrates that the pattern of critically low biomass of predators dominates most sites across all zones of Bermuda's coral reef system. RLS grades for Predators are generally more favourable nearshore, possibly due to protection from spear-fishing, while a trend in an increase of sites with poor to critical predator biomass levels increases with distance from shore and with depth down the forereef..

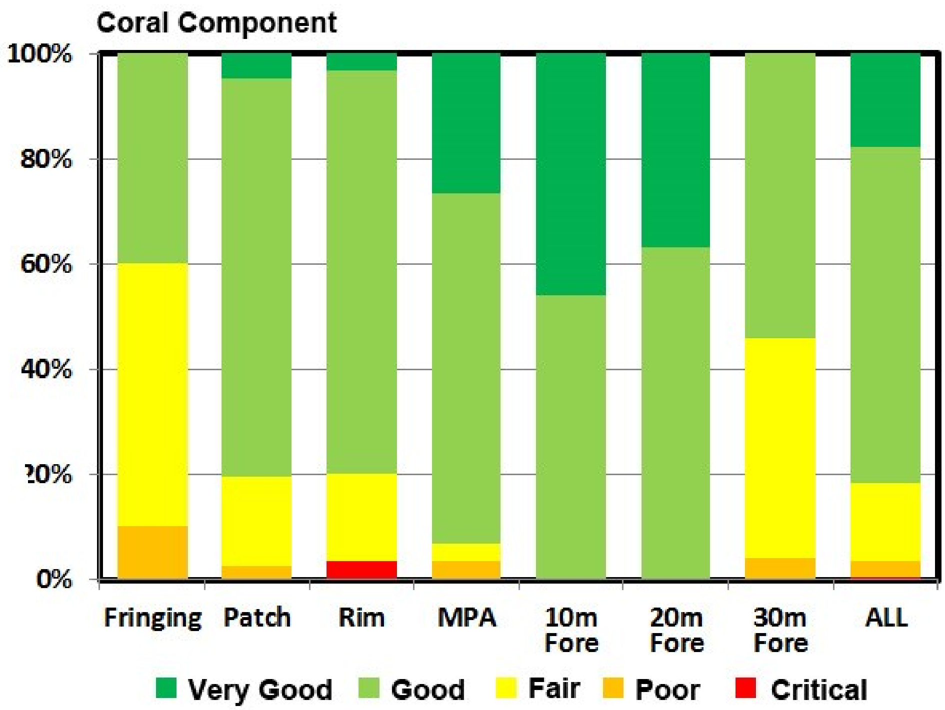

Fig. 33. Proportion of reefs within each reef zone that were ranked according to the five categories of reef condition for the Hard Coral component of the Sea Life Index

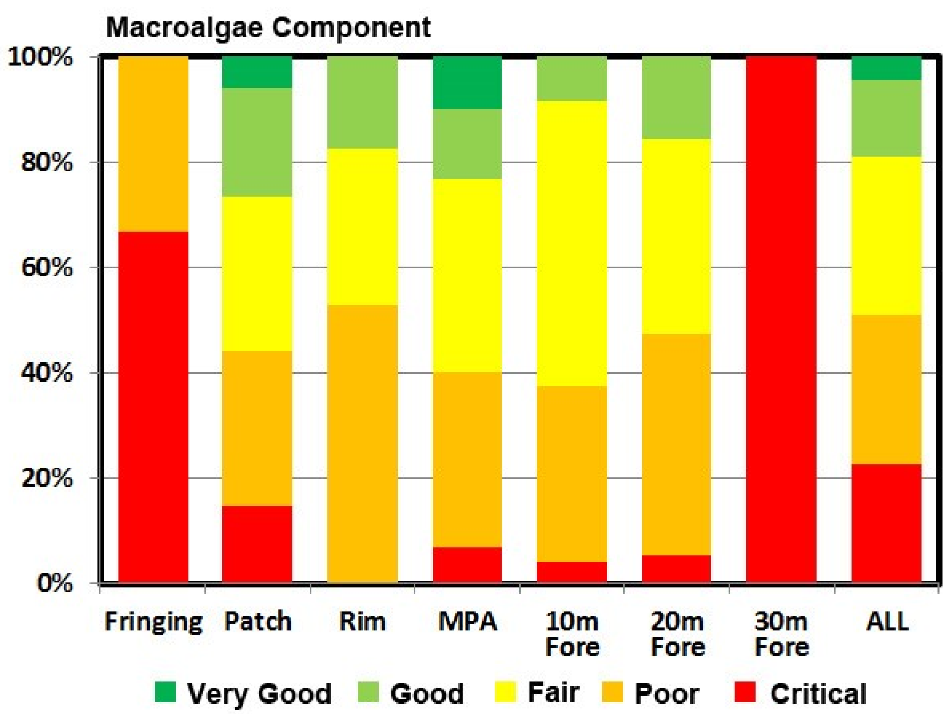

Fig. 34. Proportion of reefs within each reef zone that were ranked according to the five categories of reef condition for the Fleshy Macroalgae component of the Reef Life Score.

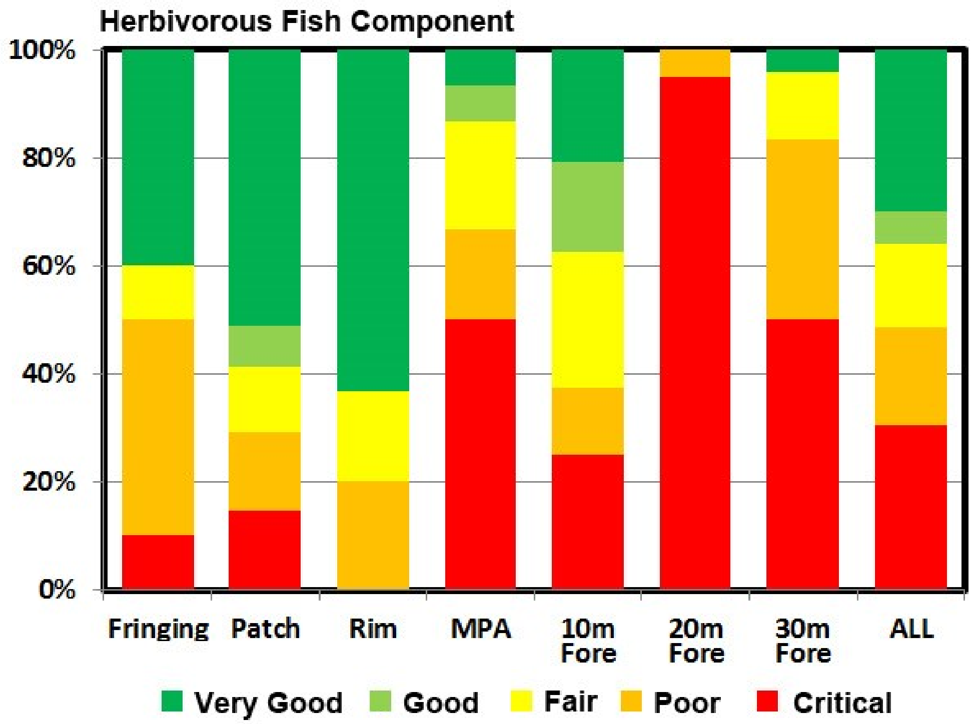

Fig. 35. Proportion of reefs within each reef zone that were ranked according to the five categories of reef condition for the Herbivorous Fishes component of the Reef Life Score.

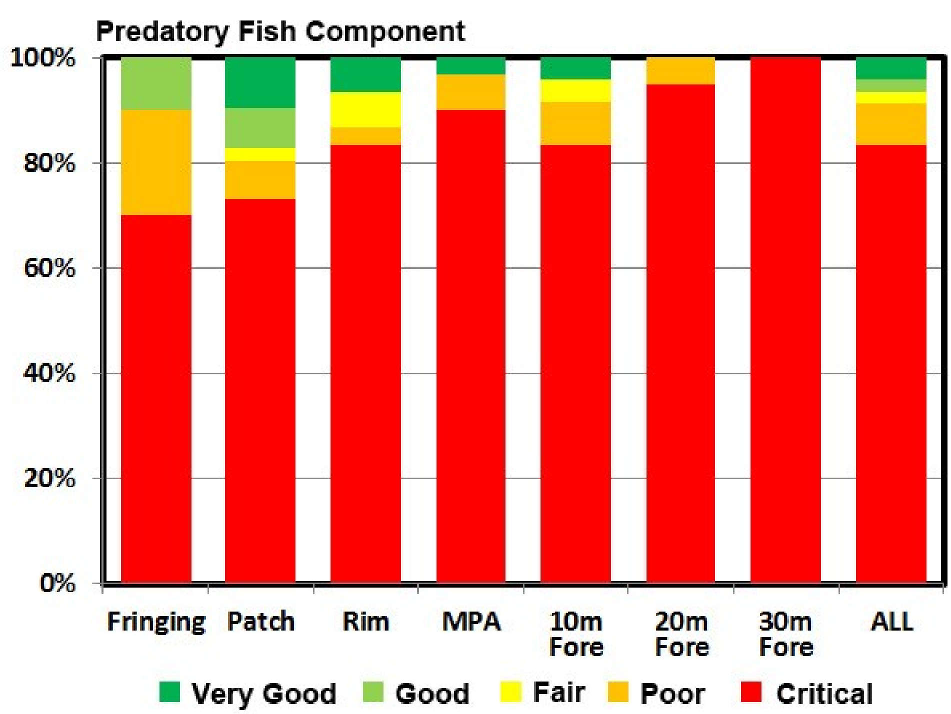

Fig. 36. Proportion of reefs within each reef zone that were ranked according to the five categories of reef condition for the Predatory Fishes component of the Reef Life Score.

Sea Life Index

The proportion of sites with each Sea Life Index score within each reef zone are plotted in Fig. 37. Proportion of reefs within each reef zone that were ranked according to the five categories of reef condition of the Sea Life Index., below, and as separate maps for the Fringing Reef Zone (Fig. 30), the Patch Reef Zone (Fig. 31) and Rim Reef Zone (Fig. 32). The average overall Sea Life Index score for each zone, and for the entire reef platform, is presented in Table 13, below.

Overall Bermuda's reefs Sea Life Index score of reef condition is 2.69 out of 5, which equates to "Fair". Zones with a higher proportion of reefs in the "Good" and "Very Good" categories are within the Patch (Lagoon), Rim, and 10-m Forereef zones. Reefs in the Fringing zone, and within the 20-m and 30-m Forereef zones have a higher proportion of reefs in the "Poor" classification, which reduces the overall SLI score for Bermuda.

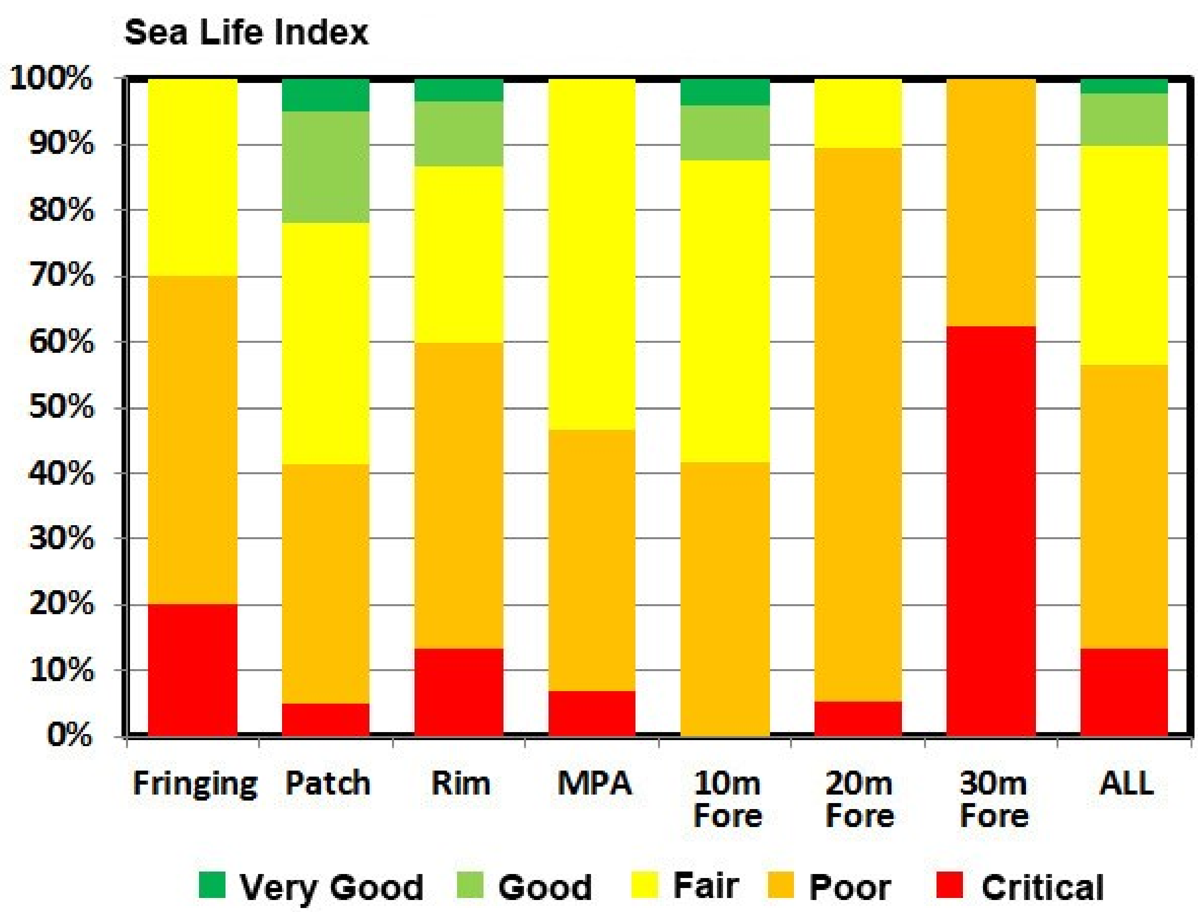

Fig. 37. Proportion of reefs within each reef zone that were ranked according to the five categories of reef condition of the Sea Life Index.

Table 13. The Component and Cumulative Sea Life Index score for each zone, and for the entire Bermuda Reef Platform.

	Fringing Reefs	*Lagoonal Patch Reefs*	*Rim Reefs*	*MPA*	*10m Forereef*	*20m Forereef*	*30m Forereef*	**Entire Bermuda Reef Platform**
Hard Coral RLS	*3.30 Good*	*3.83 Good*	*3.77 Good*	*4.17 Good*	*4.46 V Good*	*4.37 V.Good*	*3.50 Good*	**3.95 Good**
Fleshy Macroalgae RLS	*1.33 Critical*	*2.74 Fair*	*2.65 Fair*	*2.87 Fair*	*2.67 Fair*	*2.63 Fair*	*1.00 Critical*	**2.50 Fair**
Herbivorous Fishes RLS	*3.20 Fair*	*3.66 Good*	*4.07 Good*	*2.03 Poor*	*2.96 Fair*	*1.05 Critical*	*1.75 Critical*	**2.87 Fair**
Predatory Fishes RLS	*1.50 Critical*	*1.73 Critical*	*1.43 Critical*	*1.20 Critical*	*1.33 Critical*	*1.05 Critical*	*1.00 Critical*	**1.36** Critical
Cumulative Sea Life Index	**2.35 Poor**	**3.02 Fair**	**3.01 Fair**	**2.57 Fair**	**2.85 Fair**	**2.28 Poor**	**1.81 Poor**	**2.69 Fair**

The range of aggregated RLS of the Sea Life Index that correspond to each reef condition.

SLI	**Critical**	**Poor**	**Fair**	**Good**	**Very Good**
Score Range	1.00 to 1.79	1.80 to 2.59	2.60 to 3.39	3.40 to 4.29	4.30 to 5.00

Discussion

Baseline assessment of hard corals, fleshy macroalgae, herbivorous fishes and predatory fishes across the 10-m, 20-m and 30-m forereef allowed us to calculate an index of coral reef condition, the "Sea Life Index", for each zone of this 400-sq km coral reef system that surrounds the North Lagoon and island of Bermuda (Table 13). The 10-m zone received a SLI Grade of 2.85, which is "Fair". The 20-m depth zone received a lower SLI Grade of 2.28, or "Poor", and the 30-m forereef zone received a SLI Grade of 1.81, also "Poor".

Examination of each ecological parameter across zones (Table 13) illustrates clearly that there exists a system-wide lack of predatory fishes, low biomass of herbivorous fishes across the entire 20-m and 30-m zones, and high cover of fleshy macroalgae across the 30-m zone. Conversely there also exists a platform-wide pattern of high (Good to Very Good) coverage of hard corals and generally low cover by fleshy macroalgae except the zone closest to shore and the deepest zone surveyed. Cumulatively, all four ecological parameters are important components of positive reef condition, and this platform-wide analysis indicates that both the lagoonal and forereef habitats of Bermuda are in poorer condition than is generally assumed prior to this baseline assessment (Lewis 1986, Nyström, Folke and Moberg 2000, Hughes et al 2007, Mumby et al 2014).

The 10-m zone reefs (Fig. 4) varied highly in overall reef condition from site to site (Fig. 19, Table 10) with some reefs classified as "Very Good" or "Good", while others are in the "Poor" condition. The patchiness of predatory fishes across sites is driving this pattern of overall reef condition at the 10-m depth.

At 20-m depth, coral reefs displayed less variability in overall reef condition compared to the 10-m reefs. Almost all reefs were classified as "Fair" (Fig. 26, Table 11) zone-wide lack of both predatory fishes and herbivorous fishes, despite high coral cover and generally low fleshy macroalgae levels, were the causes of the low reef condition scores across the 20-m depth zone. The lower biomass of herbivorous fishes may be due to natural zonation patterns by this guild of reef fishes, which are well documented in the Caribbean region (e.g. Lewis and Wainwright 1985, Nemeth and Appeldorn 2009). These studies demonstrate that herbivorous fishes may actively congregate to feed in shallower water where high current speeds and high light conditions promote the growth of edible macroalgae (Stewart and Carpenter 2003), relative to 20-m and 30-m depth zones where light is lower and water flow is slower.

Reefs within the 30-m depth zone (Fig. 6) were found to exhibit "Poor" to "Fair" reef condition (Table 12). Hard coral cover was generally ranked as "Fair" to "Good", but fleshy macroalgae cover was very high (i.e. Critical) and the biomass of both Herbivorous Fishes and Predatory Fishes was low (Poor) to very low (Critical). The ecology of reefs within the 30-m depth zone is not well studied, and the relative roles that herbivorous fishes play in controlling macroalgae cover in this depth zone are not well documented. Additionally, this zone only was assessed for fish with the use of a towed video camera array which may have under-represented fish biomass. Branching corals, such as *Madracis decactis*, were more abundant at the 30-m depth (Fig. 11, unpublished species data in Appendix). These same corals dominate many Caribbean shallow water habitats where herbivorous fishes are rare but competition between hard corals and macroalgae is intense. It may be that these branching corals are better able to persist in areas of low fish herbivores due to the commensal herbivorous crabs that generally live within branching coals and which may allow branching corals to persist despite overgrowth by fleshy macroalgae (Coen 1988, Stachowicz and Hay 1999).

By completing the analysis of the forereef zones and adding the Sea Life Index scores from these zones to new scores calculated from the baseline data collected across the Rim, Lagoonal and Fringing reefs in previous BREAM surveys, we were able to present in this report the overall Sea Life Index Grade for the entire 750 sq km Bermuda Platform). The Bermuda Platform received at grade of 2.69 overall, or "Fair". As stated throughout this report, the relative low reef condition grade for Bermuda's reefs is predominantly driven by the system-wide lack of predatory fishes across all zones both in the lagoon and on the forereef, relative to standard levels of biomass based on historical levels of predatory biomass both in Bermuda (Bardach 1959) and across the Caribbean (Myers and Worm 2003).

The inclusion of the 30-m zone, which was found to have particularly low SLI due to high cover of macroalgae, and low biomass of both herbivores and predators does reduce the overall SLI. However, we feel that the 30-m depth zone should be included since these reefs represent roughly 25% of the overall area of the Bermuda Reef Platform, especially along the western and northern sides where they form broad reef terraces.

The data in this report represents the first baseline data for the whole Bermuda Reef Platform. Fringing, lagoonal and rim reefs were surveyed in the years 2004 to 2007, while the forereef was assessed in 2009-2010. Comprehensive assessment across all zones over the same time period is required to determine whether reef condition changed in these zones since the survey periods. BREAM has carried out comprehensive monitoring surveys across sites located from the fringing reef, across the lagoon, along the rim and the 10-m zone in 2015 and 2016 (Murdoch in prep).

Bermuda's SLI Grade of 2.69 is similar to the identically calculated SLI score for the countries of the Meso-American Reefs of Belize, Guatemala, Honduras and Mexico. In 2012 their scores ranged from 1.9 (Poor) to 3.0 (Fair) (www.healthyreefs.org). While Bermuda's reefs are located in the middle of the North Atlantic, those of Meso-America are barrier or atoll reefs located on the eastern side of Central America, in the Caribbean Sea. Both regions face some similar sources of reef impact, especially threats from overfishing. However, the Meso-American reefs are also exposed to river run-off and support a broader range of coral species and dominance by branching and plating corals, which are ecologically different from the dominant dome-shaped corals found in Bermuda.

Implications

The critically low biomass of predatory fishes across all habitats and depth zones serves as a strong indication that Bermuda's coral reefs are not in as good an ecological condition as is generally assumed, and that human actions, such as fishing, are the cause. Predatory fishes remain the focus of both commercial and recreational fisheries. Groupers and snappers are targeted in all habitats and zones, from the shoreline to the 200-ft (60-m) platform edge. Species of grouper, including Nassau grouper, which were the mainstay of our fisheries only 40 years ago, are ecologically extinct to the point where the sighting of single individuals is cause for excitement (Butler et al 1993). Black grouper are considered by many to have recovered in abundance, but the surveys in this report demonstrate they are still rare at all depths and in all areas. Both Nassau and Black grouper play an important role on the reef in controlling the abundance of smaller parrotfishes. This provides a competitive relief to larger species of parrotfish, which benefits hard corals and overall reef condition because larger species of parrotfish eat more fleshy macroalgae, compared to smaller parrotfish (Mumby et al 2006; 2011).

Smaller groupers such as red hind, coney and graysby are also rare, as were gray snappers, schoolmasters and other snapper species. One might expect, due to the low biomass of large predators, that these smaller predators would be more abundant, since large groupers are the primary predator on the smaller grouper (Chiappone et al 2000, Mumby et al 2012). However, the lack of biomass of the small predators as well indicates that fishing pressure is also removing these fishes from the marine environment across the entire Bermuda platform. The removal of smaller predatory fishes across the region is likely to have a system-wide impact on the condition of the reefs (Smith 1959).

Smaller predatory fishes play a vital role on the reef in controlling the impacts to hard corals caused by territorial herbivorous damselfishes, of which there are three species in Bermuda. These damselfishes eat plants like parrotfishes and surgeonfishes do, but instead of grazing across the reef, damselfish develop, tend and guard a lawn of turf and fleshy macroalgae. It is advantageous for the damselfish to create this lawn on reef rock that is not already encrusted or inhabited by other kinds of reef organisms, such as sponges and corals. Instead, damselfish remove the living tissue of hard corals and take advantage of the freshly exposed coral skeleton to grow their algal lawn (Kaufman 1977). This process can cause extensive damage to hard corals within the 2- to 3-m diameter territory of each damselfish. When damselfish are abundant this process can scale up to the entire surface of a patch reef, with many corals damaged either partially or completely. Damselfish also negatively affect the recruitment of new corals to coral reefs in the following manner. The turf algae farms that damselfish produce are composed of filamentous turf algae. When tended by damselfish, these turfs form thick lawns, which are protected from herbivory from other plant-eating fishes such as parrotfish. Juvenile corals have been shown to be less capable of settling onto reef rock if the turf lawn is thicker (~4 mm instead of ~2 mm), and corals that do settle are more likely to perish before reaching large size (Arnold et al 2010). Reefs cannot persist if new corals cannot recruit to the reef surface, as recruitment of new cohorts of corals sustains the population of the hard corals found on them otherwise.

Smaller predatory fishes are the natural predator of damselfish, and smaller groupers and snappers prevent damselfish from becoming over-abundant and damaging large areas of reef. If people overfish these smaller predatory fish, however, as we have shown in this report that we have done in Bermuda, then the damselfish are not kept in check and large areas of coral reef can be damaged. The last three years of BZS Reef Watch reports provides broad-scale evidence that such an impact of damselfish to coral reefs is occurring within the lagoon over an area of several 10s of sq km (Murdoch 2013, 2014b, 2015)..

Recommendations

Healthy coral reefs can only protect the island from storms, produce habitat for fishes and maintain water clarity when coral cover is high. We have shown in this report that the condition of our coral reefs across the entire reef platform is directly affected by the manner in which we regulate our fisheries. Depletion of predatory fish stocks causes cascading impacts throughout the coral reef system, affecting the abundance of the herbivorous fishes, hard corals and macroalgae. Commercial and recreational fishing constitute only **0.7%** of the annually contributed economic value generated by the services provided by Bermuda's coral reefs to our society (Sarkis et al 2013, van-Beukering et al 2015). If not properly regulated or enforced, overfishing of predatory fishes by the commercial and recreational fishers will continue to have an island-wide and dominating impact on the overall capacity of our coral reef to provide the rest of the economic services, including tourism experiences and protection of our coasts from storms

Table 14. The annual Total Economic Value of Bermuda's coral reefs, based on the value of six ecosystem services (Sarkis et al 2013).

Ecosystem Service	**Average value (million USD)**	**Contribution to TEV**
Tourism	405.9	56%
Coastal protection	265.9	37%
Recreation & Cultural	36.5	5%
Amenity	6.8	1%
Fishery (commercial & recreational)	4.9	0.7%
Research & Education	2.3	0.3%
Total annual value (TEV)	**722.4**	100%

It is recommended that current or new management options pursue the following broad management strategies:

A. Restoration of reef predator populations

1. Enhance the stocks of groupers by introducing a limited ban on the capture and sale of Black groupers during their spawning period (as we currently do with spiny lobster), based on evidence of the timing of their maximum aggregation at spawning sites.
2. Consider bag and size limits on grey snappers, schoolmaster snappers, yellowtail snappers, graysbys and coneys.
3. Expand our knowledge of juvenile predatory fish habitats, which are generally within the lagoon (patch reefs), along the shore (nearshore), and within enclosed bays (inshore). Many species of offshore reef fish, including predatory fish species, start life by settling as juvenile fish to coastal habitats, only to move offshore as they mature.
4. Reduce coastal development impacts to the marine environment, as many juvenile predatory fishes are found the inshore and nearshore waters first before they move to outer reef areas.
5. Design coastal structures so that they provide additional habitat for juvenile and adult fishes. For instance, rough surfaces can be sculpting into dock surfaces or by construction with cobble, intertidal pools can be inset into dock surfaces, and clusters of thin vertical structures mimicking mangrove habitat can be installed under docks. These habitat supplements can increase the range of fish that live near built marine structures (reviewed in Murdoch 2013).

B. Develop marine spatial planning approaches for enhanced conservation benefits

Protected areas act as a marine resource "banks" and provide "interest" in the form of continuously available fishes for commercial and recreational harvest, through the spill-over effect, and enhanced reproductive output. We recommend the expansion in the distribution of protected areas to include inshore and coastal reef, mangrove and seagrass habitat, as well as areas of lagoonal patch reefs, for closure and protection. Research indicates the value of these marine areas as juvenile habitats, and their current threatened status due to a lack of smaller predatory fishes and high damselfish densities Damselfishes persistently attack corals and their populations can be controlled by increasing predator populations. Networks of lagoonal reefs that form continuous connections between habitats close to shore and outer reef habitats at the rim and forereef play an important role by allowing fishes to transition from zone to zone throughout their life cycle. In addition, networks of reefs support more biodiversity compared with isolated reefs.

<u>The relative threat of Pacific lionfish</u>

The threat caused by the system-wide removal of predatory fishes has far greater implications about the present and future condition of our reefs than does the introduction and impacts of the Pacific Lionfish. Lionfish were not detected in our scientific fish survey transects across all sites described in this report. Only two lionfish were observed at two of the 178 of the sites surveyed in 2009-2011, and still appear to be in very low abundance across the lagoon and rim reef in 2013-2015 (Goodbody-Gringley et al 2015, Darwin report). Lionfish are caught annually in Bermuda, but at levels which would be considered exceptionally low abundance for a commercial species, especially within the lagoon where they could inflict the greatest damage. Lionfish are found to be in higher abundances below 40-m (120-ft) depth and peak in abundance at 65-m (200-ft) depth (C. Eddy pers. com.), relative to shallow waters. It is important to note that these deep rocky habitats are not coral-dominated habitats, and they do not act to provide the coastal protection from storm waves that are produced by the shallow coral reefs which are the subject of this study.

Additionally, lionfish are predatory fish in a system depleted of predators, and by being present are likely filling that predator niche in some reef zones. It seems likely that the feeding activities of lionfish on important juvenile shallow water fishes, such as parrotfish, are minimal compared to the predation pressure those same juvenile fishes faced up until the 1970s, when Bermuda supported high densities of several large and mid-sized grouper species and snappers (Bardach 1959). Bermuda's shark population, not the subject of this report, have also been subject to system-wide depletion since the 1970s.Thus, the loss of the entire reef predator guild, except very small predatory fish (barred hamlets) and some meso-predators (trumpetfish), grossly overshadows the predation pressure now hypothesized by others to occur due to the sparsely distributed lionfish.

Moving Forward

The baseline data collected by BREAM in this project will be used to guide the BREAM Reef Resilience Monitoring Project, which is a comprehensive and long-term monitoring programme of our reef system. Continuous, broad-scale yet statistically rigorous monitoring of fish and benthic condition (such as hard coral cover) is vital for the evidence-based management and conservation of Bermuda's marine resources and biodiversity.

We have provided open, public access to all of the information in this report, as well as all other BREAM AGRRA reef and fish data, via both Bermuda-based libraries and through the online database at www.BermudaBREAM.org. We made our research data publicly available because it is vital that Bermuda's fishes and marine habitats maintain or improve their ecological condition across the entire platform, and it is in the best interests of the Bermuda public to ensure that reef condition remains high. It is also very important that Bermudians understand both the vitality of Bermuda's reef system, and its fragility. The best ways to do so are to provide the Bermuda public with timely information on the status of the reef system and to empower Bermudians to be able to accurately assess and understand the condition of coral reefs and their fishes themselves, so they are no longer solely reliant upon research scientists nor the government to provide the critical reef health information.

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Baseline BREAM data for Bermuda coral reefs and fishes is publicly available at:
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