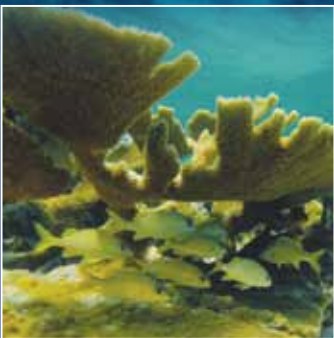


# Towards Reef Resilience and Sustainable Livelihoods



A HANDBOOK FOR CARIBBEAN CORAL REEF MANAGERS



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FORCE project, University of Exeter, Marine Spatial Ecology Lab,

College of Life and Environmental Sciences, Exeter, Devon UK

[www.force-project.eu](http://www.force-project.eu)

# Towards Reef Resilience and Sustainable Livelihoods

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Juan P Carricart-Ganivet, John Charlery, Charlie Dryden,  
Fleur C van Duyl, Susana Enríquez, Joost den Haan, Roberto  
Iglesias-Prieto, Emma V Kennedy, Robin Mahon, Benjamin  
Mueller, Steven P Newman, Maggy M Nugues, Jorge Cortés  
Núñez, Leonard Nurse, Ronald Osinga, Claire B Paris,  
Dirk Petersen, Nicholas V C Polunin, Cristina Sánchez, Stijn  
Schep, Jamie R Stevens, Henri Vallès, Mark J A Vermeij,  
Petra M Visser, Emma Whittingham, Stacey M Williams





## FOREWORD

*Too often people say, 'We really should do something about the health of our coral reefs'. Caribbean coral reefs have declined from 50% cover in the 1970s to 10% today and finding solutions to halt this trend has to be a top priority.*

*In response, the largest multi-disciplinary team of marine scientists from the Caribbean, Europe and Australia spent five years using state-of-the art research to produce this most up-to-date and comprehensive handbook for reef managers.*

*Determined to make a positive difference to help safeguard our Caribbean reefs for those who live, work or simply love being by the sea, this unique reference explains why a scientific basis for managing coral reefs is needed to tackle unprecedented levels of human pressure and uncertainty around impacts of future climate change.*

*This manual succeeds in presenting complex information in an interesting and easily readable format so managers and anyone who wants to make a change can identify key issues, possible options for tackling them and management recommendations.*

*What is your vision for change? Let's start working towards that using this handbook.*

*Having the most beautiful office in the world – a hammock on Necker overlooking the British Virgin Islands – and starting my day with a swim I am reminded of the importance of looking after our seas. Many of us want to be 100 per cent fit and healthy so why not extend this to an ecosystem with the greatest biodiversity in the ocean, coral reefs?*

*If we are going to conquer global challenges such as food insecurity, poverty and climate change there must be more cooperation, collaboration and shared learning among those serious in securing the future of our planet. More than seventy percent of our planet's surface is covered by the ocean and an estimated 75% of the world's human population are expected to live on the coast. Reefs will be even more important as a future source of food and livelihood for many dependent on the Caribbean's beautiful coral reef ecosystem.*

*The way we co-exist with our natural environment, strengthen fragile societies and support vulnerable populations is the very foundation of a sustainable future and reflects the core values of Virgin Unite – our non-profit foundation of the Virgin Group.*

*Like my team at Virgin Unite, the team behind this book have focussed their creativity, passion and commitment to providing guidance for managers to aid decision-making on actions that have a positive impact for tomorrow.*

*To succeed in securing a healthy future for the Caribbean's coral reefs we must look at this underwater world through a different lens; by acting today on the recommendations in this book you can help transform the challenges in to opportunities. Let's do it!*



Sir Richard Branson  
Founder of the Virgin Group





## PREFACE

*In 2009, the European Union funded a collaborative research programme between scientists in the Caribbean, Europe, Australia, and the United States. The project was entitled 'Future of Reefs in a Changing Environment' (FORCE) and sought to help coral reef managers undertake their important work by providing targeted scientific study of the issues, and identify tools and solutions. The research team was broad, with representation across natural and social sciences, a vital combination given that management mostly comprises the modification of peoples' behaviour and because reefs are important to so many peoples' livelihood and quality of life.*

*The content and format of this book was developed with the generous input of reef managers throughout the region. Our intent was to cover a wide range of critical topics and provide policy and management options throughout. In doing this, we draw on thousands of scientific studies, not just those undertaken by the FORCE project teams. However, where we felt that certain topics had been covered adequately by other resources we opted to point readers towards those resources and only provide a brief summary here.*

*The broad authorship reflects the input of many researchers to this book. Jason Flower devoted a year of his life to coordinating, writing and editing sections with the collective of authors. He worked closely with the Project's manager, Rosanna Griffith-Mumby, to help deliver the vision for the book. The core writing team are listed at the front of the authorship and followed by the wider authorship – in alphabetical order – all of whom made critical contributions.*

*If you'd like to find out more about the project, please visit [www.force-project.eu](http://www.force-project.eu) where you'll also find links to many resources including our Caribbean-wide online geographic information system (GIS) with specially-prepared datasets to aid reef management.*

*The FORCE project led to many new friendships (including a marriage!) and research partnerships and certainly highlighted the challenges and excellent work being done to manage reefs throughout the Caribbean. We hope you find the book and associated tools useful – we certainly enjoyed preparing them.*

*Sincerely*



*Professor Peter J Mumby  
University of Exeter & The University of Queensland  
FORCE Project Coordinator*



*Caribbean reef managers and FORCE group at GCFI  
conference in Corpus Christi, Texas, 2013*

## FORCE PRINCIPAL INVESTIGATORS

- Stephen J Box, Centro de Estudios Marinos, Honduras
- Juan P Carricart-Ganivet, El Colegio de la Frontera Sur & Universidad Nacional Autónoma de México (UNAM), Mexico
- Ben Cattermoul, Integrated Marine Management Ltd, UK
- Iliana Chollett, University of Exeter, UK
- Jorge Cortés Núñez, Centro de Investigación en Ciencias del Mar y Limnología (CIMAR), University of Costa Rica, Costa Rica
- Fleur C van Duyl, Royal Netherlands Institute for Sea Research (NIOZ), The Netherlands
- Susana Enríquez, Universidad Nacional Autónoma de México (UNAM), Mexico
- Maoz Fine, Bar-Ilan University & Interuniversity Institute for Marine Sciences, Israel
- Clare Fitzsimmons, Newcastle University, UK
- Roberto Iglesias-Prieto, Universidad Nacional Autónoma de México (UNAM), Mexico
- Robin Mahon, Centre for Resource Management and Environmental Studies (CERMES), University of the West Indies, Barbados
- Erik Meesters, Institute of Marine Resources and Ecosystem Studies (IMARES), Wageningen University, The Netherlands
- Peter J Mumby, University of Exeter, UK & University of Queensland, Australia
- Maggy M Nuges, Leibniz Center for Tropical Marine Ecology (ZMT), Germany & University of Perpignan, France
- Leonard Nurse, Centre for Resource Management and Environmental Studies (CERMES), University of the West Indies, Barbados
- Ronald Osinga, Wageningen University, The Netherlands
- Hazel A Oxenford, Centre for Resource Management and Environmental Studies (CERMES), University of the West Indies, Barbados
- Dirk Petersen, Rotterdam Zoo, The Netherlands
- Nicholas V C Polunin, Newcastle University, UK
- Onno Roosenschoon, Alterra Wageningen UR, The Netherlands
- Selina M Stead, Newcastle University, UK
- Jamie R Stevens, University of Exeter, UK
- Philip Townsley, Integrated Marine Management Ltd, UK
- Mark J A Vermeij, CARMABI, Curaçao
- Petra M Visser, University of Amsterdam, The Netherlands

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# Caribbean Coral Reefs Ecological History and Biogeography



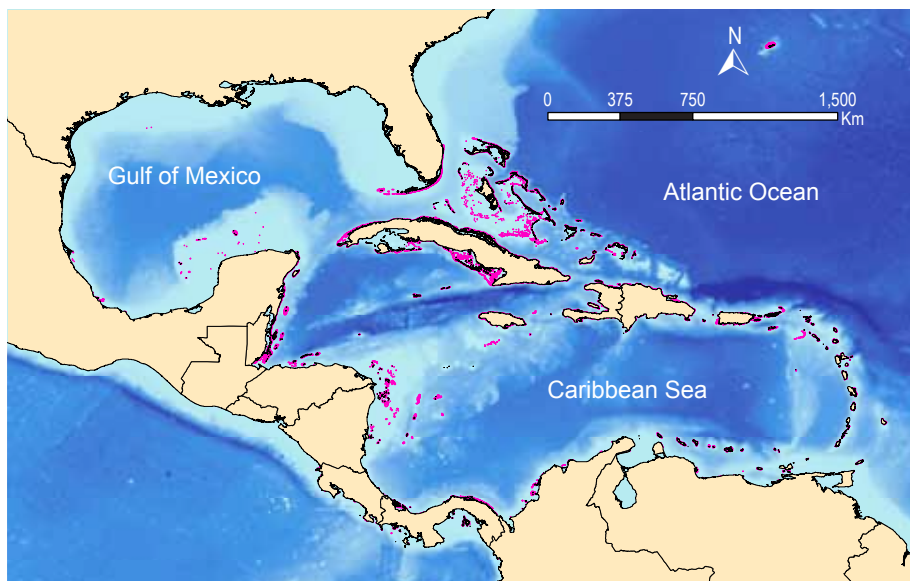


*Caribbean coral reefs account for only 7% of the world total coral reef area but play a vital role in the economy of the region and the livelihoods of millions of people who depend upon the reefs for income and employment.*

*Coral cover has declined from 50% in the 1970s to less than 20% today, potentially reducing the ability of the reefs to provide the ecosystem services that many people rely upon, including habitat for reef fisheries, tourism appeal and coastal defense from storms. Coral loss has been accompanied by an increase in fleshy macroalgae (seaweed) across much – though not all – of the region. Many impacts have contributed to this shift from coral to macroalgal dominated reefs including disease, coral bleaching, hurricanes, overfishing, and land-based run-off (bringing sediment, pollution and nutrients).*

*Human impacts on reefs in the Caribbean predate the arrival of European settlers in the 15th century, but it is only since the 1970s that large declines in coral cover across the region have occurred. These declines were in part due to outbreaks of disease which wiped-out much of the branching acroporid corals and long-spined sea urchins during the late 70s and early 80s. Overfishing and land-based run-off due to human development fundamentally weakened the ability of the reefs to recover from these impacts. Since the 1980s, many reefs have declined further because of hurricanes, major bleaching events in 1995, 1998, 2005 and 2010, and coral diseases. There is considerable variation in the state of reefs across the region. A few reefs still have coral cover above 50% but others have slipped below 10%. Deep coral reefs (those greater than 30 m depth) may provide a refuge to corals from some of the impacts that have affected shallower reefs. However, reducing local human impacts, which have been affecting many reefs for decades if not centuries, is vital to enable coral reefs to withstand the worsening impacts of climate change. While climate change is already impacting coral reefs, reef management is by no means futile and more important than ever.*

## THE LONG VIEW



Locations of coral reefs (pink) within the Caribbean.

### Geological time-scale development of Caribbean reefs

Before looking at the effects humans have had on reefs it is useful to understand how reefs were before humans arrived. Caribbean coral reefs have evolved in isolation from those in the rest of the world ever since the land that is now Central America rose up from the ocean, cutting the connection between the Atlantic and Pacific Oceans about 3 million years ago. Subsequent ice ages wiped out many coral reefs, but enough corals remained to recover and rebuild the reefs (Spalding 2004). Without any connection to other coral reefs outside the Caribbean basin, corals evolved in isolation so that most Caribbean corals are unique to the region, but the diversity of corals is much lower, with only 62 stony coral species compared to 719 in the Indo-west Pacific (Spalding et al. 2001).

Studies of fossilized corals have shown that Caribbean reefs were stable in their community composition and zonation pattern for at least 125,000 years (Pandolfi & Jackson 2006; Precht & Aronson 2006). Reefs were typically dominated by *Acropora palmata*, which occurred in the shallow reef crest zone, *A. cervicornis*, occurring in the shallow reef slope or fore-reef, *Orbicella spp.*, principally *O. annularis*, occurring on the reef slope and *Agaricia spp.* occurring on the deep reef slope (Goreau & Goreau 1973; Liddell & Ohlhorst 1987; Pandolfi & Jackson 2006). The two branching coral species *A. palmata* and *A. cervicornis* are particularly important as they provide vital three dimensional structure to many reefs (Pandolfi & Jackson 2006).



*Acropora palmata*.



*A. cervicornis*.



*Orbicella annularis*.



*Agaricia spp.*

# HUMAN INFLUENCES ON CARIBBEAN REEFS OVER 2000 YEARS: OVERFISHING AND LAND USE CHANGE

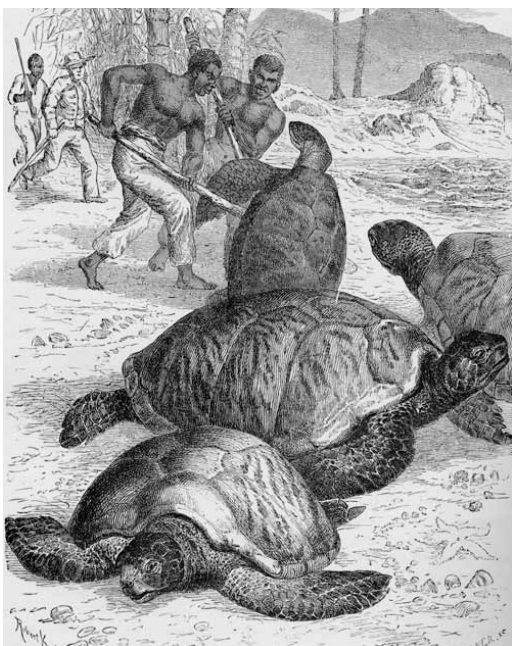
## Before Columbus

Archaeological evidence from pre-historic times strongly suggests that the early settlers to the Caribbean were over-exploiting both land and marine resources long before the arrival of Columbus in 1492 (Wing 2001b; Wing & Wing 2001). On land, ground sloths were probably hunted to extinction by the first settlers (Rouse 1992) and other large animals which were an easy food supply, such as turtles, manatees, carnivorous fish and land crabs, were overharvested (Wing 2001a; Wing 2001b; McClenachan et al. 2010). Evidence from middens (household refuse deposits) dating from over 1,500 years ago to 560 years ago shows a decrease in the size and weight of reef fish, strongly suggesting overexploitation of the easily accessible fish populations (Wing & Wing 2001).

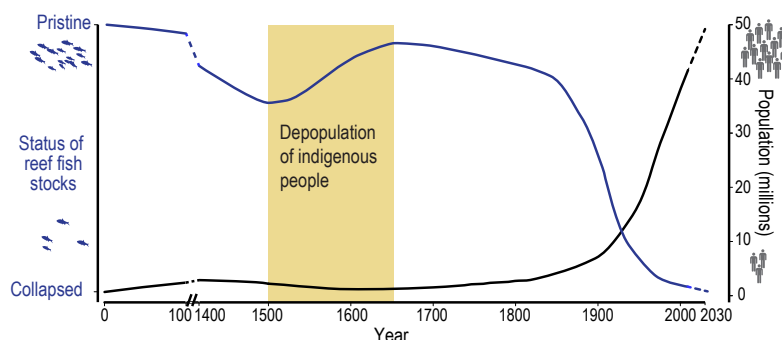
Damage to coastal marine environments through increased sediments from agricultural development may also have occurred before European conquest. Early reports from European explorers talk of well-developed agricultural systems on some of the islands including terraces and slash and burn farming practices (Columbus 1989, p.213; Wing 2001a; Sued-Badillo 2011).

## Columbus and colonization

The arrival of Columbus, followed by the Spanish conquistadores resulted in the extinction of most indigenous human populations due to conflicts, diseases and forced labour (Barker 2011). This early period of colonisation may actually have been a reprieve for the marine life in the Caribbean, as a declining human population



Early mass sea turtle harvesting in the Caribbean ca. 1883.



put less demand on the environment (Figure). The Spanish colonists relied initially on food and drink, such as salted sardines, wine and oil, imported from Spain, and later the import of livestock, primarily cattle and pigs, provided a land-based source of protein (Sued-Badillo 2011).

*Human population in the Caribbean (black) and hypothesised change in reef fish stocks (blue, after Hardt 2007). Note break in x-axis between 100 and 1400 A.D.*

With the advent of a modern plantation system in the 17th century, the populations of the islands began to increase as large numbers of slaves were brought to the Caribbean. The increasing trade brought more European sailors who harvested turtles and manatees in large numbers (Hardt 2007). Reef fish populations were largely spared until the 19th century when fishing became common as the increasing human population demanded more food sources.

Unrestrained harvesting of turtles and fish to feed the growing populations reduced fish stocks to the point where Jamaica was importing 85% of fish consumed on the island by 1881 (Jackson 1997). Turtle populations were massively reduced across the Caribbean as they provided an easily accessible food source for the new colonies. In the Cayman Islands, where turtles had been so abundant that the explorer Ferdinand Columbus wrote in 1503, "... in sight of two very small and low islands, full of tortoises, as was all the sea about, insomuch that they looked like little rocks...", the turtle fishery was exhausted by 1800 (Jackson 1997). Evidence also suggests that large herbivorous fishes may have already been rare before the 20th century (Jackson et al. 2001).

Added to the effects of overfishing would have been large increases in the amount of sediment runoff into the near-shore environment, as land was cleared for plantations on many of the islands (Jackson 1997). This trend has continued through the 19th and 20th centuries as agricultural land-use has intensified, bringing with it nutrient runoff due to fertiliser use (Carilli et al. 2009). Both sediment and excess nutrients can have detrimental effects on corals (Lewis 1984; Fabricius 2005; Cramer et al. 2012).



Harpooning a manta ray in Jamaica ca 1880.

## SHIFTING BASELINES

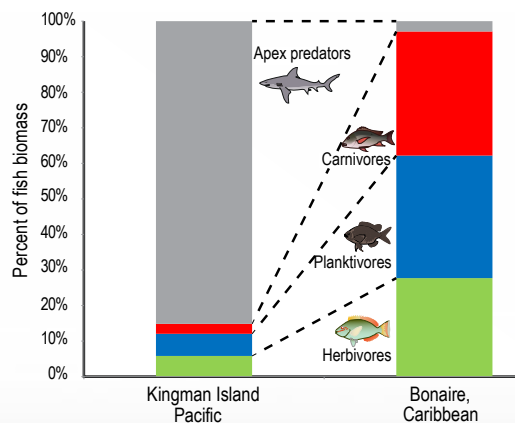
*Trophy fish caught on charter boats in Key West, Florida Keys, comparing 1956, 1985 and 2007 (bottom of the page).*



Taking the long view it is clear that coral reef ecosystems were substantially impacted before the advent of modern coral reef ecology in the 1950s. The reefs that the first marine scientists saw were not in the pristine condition that was generally assumed at the time. Generations of scientists, fishers and reef managers have accepted the state of the reefs when they first saw them as their point of reference (baseline) for a healthy reef. This has resulted in the gradual shifting of the baseline and an acceptance that degraded reefs are actually the norm (Knowlton & Jackson 2008). The problem

of shifting baselines is difficult to overcome in coral reef ecology as we have few examples left of what a healthy reef ecosystem should look like. The remote northern Line Islands in the Pacific provide a window into a relatively untouched reef ecosystem where reef fish biomass (a measure of total weight of fish) is more than double that of many Caribbean sites and most of this biomass is made-up of apex predators (Knowlton & Jackson 2008; Sandin et al. 2008). In the Caribbean large apex predators, particularly sharks and large groupers, are missing from most reefs (Ward-Paige et al. 2010) meaning that most fish biomass is made up of small carnivorous fish, such as grunts, smaller groupers and snappers, planktivorous fish, such as damselfish, and herbivores, such as parrotfish and surgeonfish (Newman et al. 2006). Even on reefs that are within well-established marine parks, such as Bonaire, apex predators are all but absent and the contrast in the composition of the reef fish compared to a pristine reef is stark. Although much of the depletion of fish populations happened outside of living memory, even the changes over the last 50 years can be seen quite dramatically in the falling size of fish caught by sport fishermen in the Florida Keys (McClenachan 2009).

*Percent fish biomass of four fish functional groups on the pristine Kingman Island in the Pacific and Bonaire in the Caribbean which is within a marine park.*



## CATASTROPHIC LOSS OF KEYSTONE SPECIES

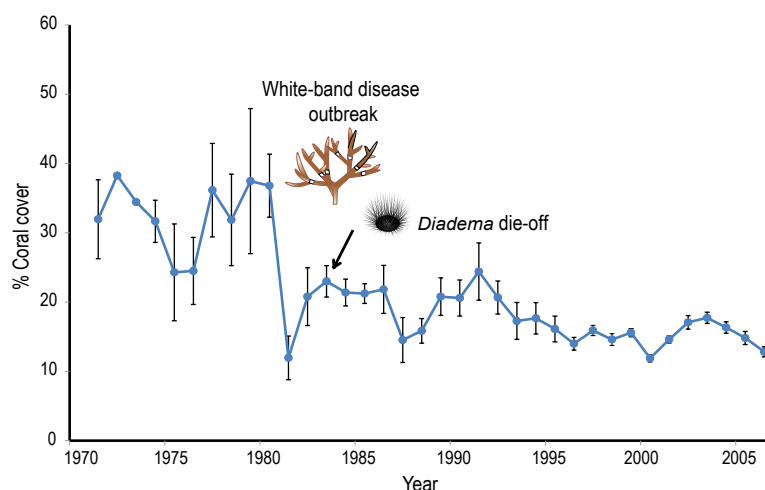


Mass mortality of *Diadema* and *Acroporids* during the late 1970's until early 80's has changed the face of Caribbean coral reefs.

Despite the historical loss of reef fish stocks, coral populations appear to have been relatively healthy until the late 1970s. Coral cover data for the period up until the 1980s has considerable variability due to the small number of sites that were monitored at that time (Graph). However, it is clear that coral cover declined sharply from the late 1970s to the early 1980s. This decline is attributed to the mass mortality of the branching corals *Acropora palmata* and *A. cervicornis*, principally due to white-band disease (Goreau et al. 1998; Aronson & Precht 2001; Schutte et al. 2010). Until this point, these two corals had been highly abundant across the Caribbean, dominating the upper reef slopes, providing vital habitat for many fish and other reef creatures (Alvarez-Filip et al. 2009; Roff & Mumby 2012). The rapid loss of both of *A. palmata* and *A. cervicornis* is without precedent in the fossil record and has not only reduced coral cover, but also the recovery ability of reefs as they are two of the fastest growing corals in the Caribbean (Pandolfi & Jackson 2006; Precht & Aronson 2006; Perry 2012).

At almost the same time as white-band disease was decimating *Acropora*, an unidentified pathogen spread rapidly throughout the Caribbean, wiping out over 93% of the population of the long-spined sea urchin *Diadema antillarum* from 1983 – 1984 (Lessios 1988). Prior to this mass mortality, *Diadema* had been highly abundant on Caribbean reefs and were a major consumer of algae (Carpenter 1986; Lessios 1988). Following the loss of *Diadema*, only herbivorous fish remained as the major algal consumer, yet these had already been overfished in many locations. Where fishing had been high, the few remaining fish were unable to hold the growth of algae in check and many – but not all – reefs began to experience increases in macroalgae (Hughes 1994; Bellwood et al. 2004; Roff & Mumby 2012).

Following a history of overfishing, changes in land uses and the catastrophic loss of keystone species, Caribbean-wide bleaching events in 1995, 1998, 2005 and 2010 caused further coral mortality and many reefs suffered outbreaks



of coral diseases in the wake of these events (CARICOMP 1997; Wilkinson 1998; Wilkinson & Souter 2008; Eakin et al. 2010; Bastidas et al. 2012). Hurricanes have also caused considerable coral mortality and reduced the complexity of reef structures (Gardner et al. 2005; Wilkinson & Souter 2008; Alvarez-Filip et al. 2009). Coastal urbanization has continued to add stress to reefs with associated pollution, sedimentation, physical damage and fishing pressure (Mora 2008) and invasive lionfish are having significant negative impacts on reef fish populations at some locations (Green et al. 2012). Ecosystems are reaching tipping points and in most areas the chronic effects of overfishing and terrestrial run-off have weakened the natural ability of reefs to recover from acute impacts such as hurricanes, bleaching events and coral diseases (Hughes et al. 2010).

Annual average coral cover for the Caribbean region ( $\pm$  Standard Error).



Lionfish.



White-band disease.

## CURRENT STATE OF REEFS

Coral cover across the Caribbean may be as much as 50% lower than in the 1970s, though coral decline since the early 1980s has been much slower (Graph p.15; Gardner et al. 2003; Schutte et al. 2010). Gardner et al. (2003) reported a region-wide reduction in coral cover from 50% to 10% in three decades, raising serious concerns for the future of Caribbean reefs. In light of findings that proposed 10% coral cover as a critical threshold below which reefs typically erode faster than they accrete (Perry et al. 2013), it seemed likely that most reefs in the region were destined for decline. However, new research shows that when habitat is taken into consideration, coral cover is not as low as previously reported (Williams et al. in prep).

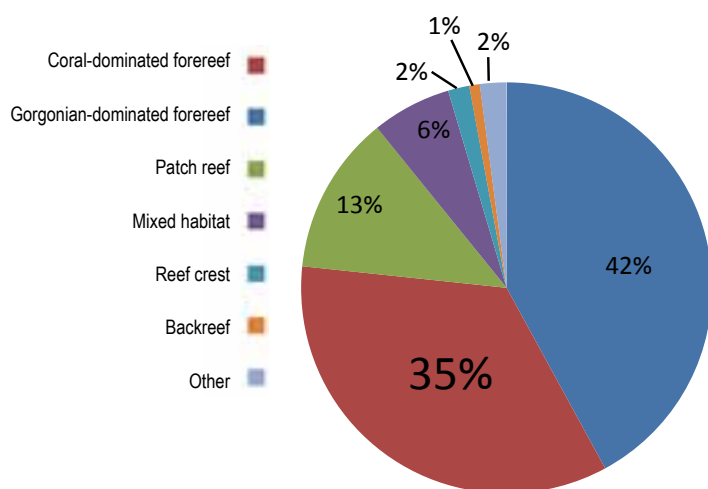
Coral reef habitat types include lagoons, back reefs, reef crests, gorgonian-dominated forereefs and coral-dominated forereefs (Harborne et al. 2006). These five distinct reef types have different structures, function in different ways and experience different physical and biological disturbances (Harborne et al. 2006). Previous meta-analyses of Caribbean wide coral cover have implicitly combined multiple reef habitats, some of which have never been coral-dominated and are naturally inhabited by gorgonians rather than hard corals. Inclusion of the habitat 'gorgonian plain' (also known as 'hardbottom') in meta-analyses leads to pessimistic assessments of average coral cover and this problem occurs because many reef surveyors do not discriminate the habitat type (typically, they simply standardise depth and reef zone, such as forereef).

Of all reef habitats, coral-dominated forereefs are the most meaningful for conservation and



*Orbicella reef.*

monitoring because they have the highest abundance and richness of organisms, greatest structural complexity and highest value for ecosystem services, such as tourism and fisheries (Mumby et al. 2008; Harborne 2009). When considering only coral-dominated forereefs, Williams et al. (submitted) found average coral cover across 92 reefs in 11 countries in the Caribbean to be 24%, more than double previous estimates of coral cover across different habitats (Gardner et al. 2003; Schutte et al. 2010). This not only provides a more optimistic baseline for the state of Caribbean reefs, but demonstrates the importance of separating habitat type when comparing among reefs. Furthermore, although many reefs have declined, a few reefs have shown signs of recovery, such as Dairy Bull Reef in Jamaica (Idjadi et al. 2010) and the Exuma Cays Land and Sea Park in the Bahamas (Mumby & Harborne 2010).



*Distribution of Gardner et al. (2003) data per main habitat, following Mumby and Harborne (1999) classification. Habitats as indicated in the source papers or according to their geographic location (available for 90% of their 263 sites). Coral-dominated and gorgonian forereefs were discriminated using wave exposure (Chollett & Mumby 2012).*



*Gorgonian plain.*

## MESOPHOTIC CORAL REEFS



Discarded chain and fishing gear on a mesophotic reef at 80m, photographed in Curacao from a submarine.



Mesophotic reef at 55 m in Bonaire.

### Deep coral refuges

One area of coral reefs that goes largely unnoticed by many people are deep reefs. Deep reefs, or mesophotic coral reef ecosystems (MCEs), are defined as any reef beyond 30 m to a depth of approximately 150 m where the corals are still light dependent (Lesser et al. 2009). They can be divided into two general categories: (1) sections of reef slopes beyond 30 m; and (2) submerged offshore banks. From 30 – 60 m the benthic communities of the reefs are similar to those in shallower reefs, but beyond 60 m they tend to be dominated by sponges and algae (Slattery et al. 2011).

Their depth means that not only are MCEs beyond the view of many scuba divers, but they also frequently escape many of the disturbances that affect shallower reefs such as bleaching, hurricanes, sedimentation and disease. They can therefore act as a natural refuge for corals against both human impacts and the predicted impacts of climate change (Bridge et al. 2013). In the Caribbean approximately a quarter of corals are found on both deep and shallow reefs, with just a few species (e.g. *Agaricia grahamae*, *Madracis formosa*), observed exclusively on mesophotic reefs (Bongaerts et al. 2010). MCEs offer a refuge not just for their own unique biodiversity but also to some corals that may eventually become locally extinct in shallower waters. However it is still debated to what extent larval movement occurs between deep and shallow reefs, and to what extent deep reefs can act as a source of reproduction (Bongaerts et al. 2010).

It might appear that deep reefs are naturally well protected from impacts and therefore don't need further protection, however mesophotic corals are highly vulnerable to sedimentation and physical damage. Most deep corals have plate-like growth forms; the most common species within the Caribbean are *Agaricia grahamae* and *A. lamarcki*, which are fragile and therefore easily broken by fishing gear and anchors. These growth forms are also prone to collecting sediment hence most mesophotic reefs are found in areas of low sedimentation and poor coastal development practices that increase sediment flows to the ocean risk smothering mesophotic corals. A further threat within the Caribbean are invasive lionfish which are found at depths greater than 100 m and consume important herbivorous fish (Lesser & Slattery 2011). Evidence from the Bahamas suggests lionfish may have already contributed to declines in coral populations at mesophotic depths (Lesser & Slattery 2011).

Protecting deep, mesophotic, reefs could therefore be included in reef management plans and marine parks might endeavor to extend beyond the easily accessible and well known shallow reefs and include MCEs. Beyond preserving coral biodiversity, protection of MCEs is important for some commercial fish species. Fishing on deep reef banks for species such as grouper and snapper is common in many areas of the Caribbean and some fish species, including groupers, migrate to mesophotic reefs to spawn (Bridge et al. 2013). Protection of MCEs present a new challenge to reef managers as many of these areas are still being discovered and may be far offshore. Nonetheless, reef management plans could aim to include MCEs or risk losing areas of coral reef that we have only just begun to understand.

## GEOGRAPHIC AND DEPTH VARIABILITY IN CURRENT REEF HEALTH

### Different changes for different reefs

In generalising, we inevitably lose detail; talking about 'Caribbean reefs' as a whole overlooks the many differences among regions, countries and individual reefs (including habitats, as already discussed). The Caribbean has 20 000 km<sup>2</sup> of coral reefs, 7% of the world's total (Map p.12 ; Spalding et al. 2001), spread across an area extending from Florida in the north to Venezuela in the south and from the surface down to depths of 100 m. Caribbean reefs span multiple environmental and governance regimes (Chollett et al. 2012; Fanning et al. 2013). Unsurprisingly the cover of most benthic organisms on coral reefs shows considerable variation across the region, with coral cover ranging from at least 34% in Bonaire to 12% in Antigua and macroalgae varying from 43% in Jamaica to 2.5% in Panama. These results present a single 'snapshot' of the variable state of reefs across the region and allow for some comparison across reefs and countries as a consistent survey methodology and survey team were used. However, like any snapshot view, only the current state, not the long-term trend, is summarised.

Further results from region-wide reef surveys found the mustard hill coral *Porites astreoides* to be the most common coral species, however *Orbicella* (formerly *Montastraea*) *faveolata* was observed to have the highest cover throughout the region at coral-dominated forereef sites. *P. astreoides* is referred to as a 'weedy' coral species as it forms small, short-lived colonies that grow quickly (Côté & Darling 2010). The replacement of the primary reef building corals,

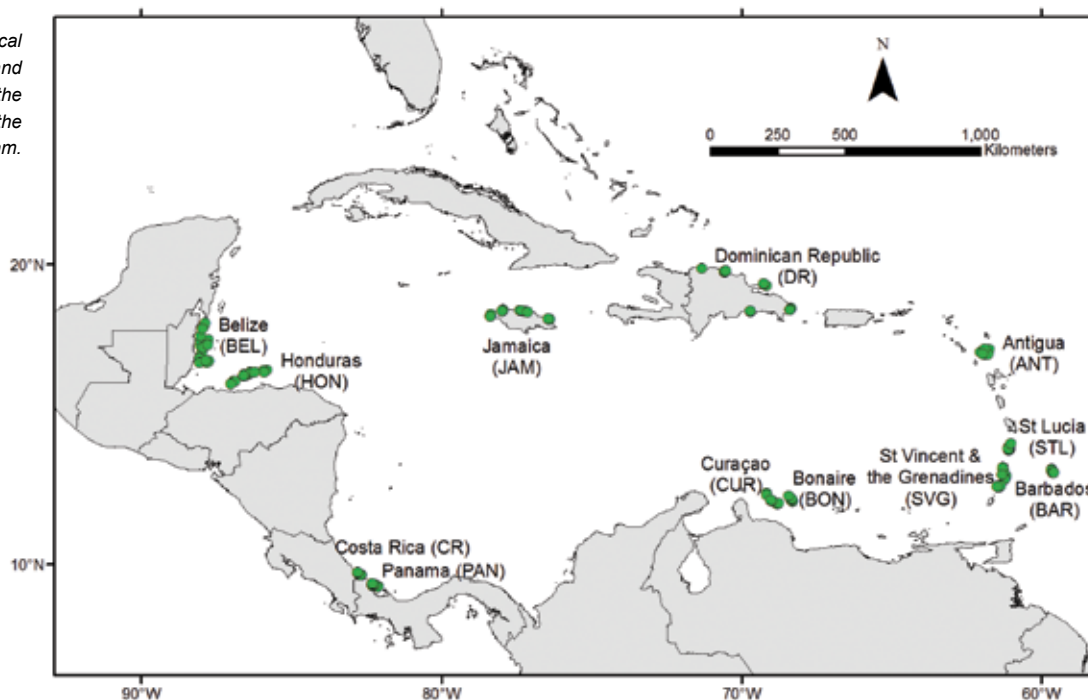


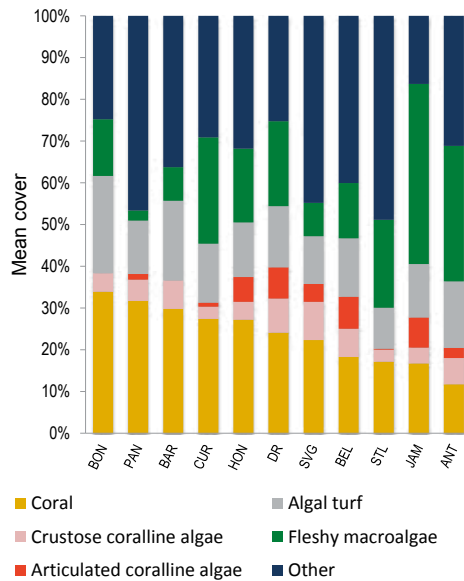
*Porites astreoides*.

*Acropora* and *Orbicella* species, with *P. astreoides* and other weedy corals has resulted in the loss of reef structure, as these corals contribute less to the reef framework (Alvarez-Filip et al. 2009).

While coral cover is most frequently the focus of reports on reef state, there is also a large geographic variability in cover and number of species of sponges and octocorals (e.g. sea fans). A new, detailed classification scheme for physicochemical environments (Biogeography Brief 1 p.22) has been developed and has been used to understand some of this geographic variation in species. For example, species richness of corals

Map of the 12 ecological survey countries and sites surveyed within the Caribbean by the FORCE team.

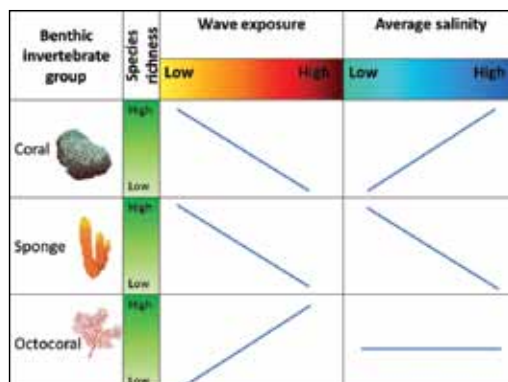




Average benthic cover on coral reef habitats in 12 countries of the Caribbean.

varies among forereef habitats, with higher richness observed at coral-dominated forereef sites characterized by lower wave energy. Similarly, species richness for sponges is highest in sheltered environments (low wave exposure) and low salinity reefs. In contrast, octocoral species richness is highest on reefs with high wave exposure.

A further issue highlighted by the recent surveys is the relatively high abundance of *Clionaid* sponges, the second highest sponge cover after the giant barrel sponge *Xestospongia muta*. *Clionaid* sponges are able to bore into the reef, weakening and destroying the structure in a process called bioerosion (Hutchings 2011). Increasing abundance of these sponges will further contribute to the loss of reef structure (Resilience Brief 7 p.46).



Change in species richness of corals, sponges and octocorals from low to high wave exposure and average sea salinity. All results from coral-dominated forereef sites.

## FUTURE FOR CARIBBEAN REEFS

Globally, the conditions for corals reefs are predicted to get worse over the coming century with more frequent and severe coral bleaching events expected due to warming seas and a reduction in the rate of reef calcification brought on by rising temperatures and ocean acidification. These effects combined with a shift to 'weedy' coral species and an increasing abundance of macroalgae and bioeroding sponges will continue to make improving the health of reefs a challenging but important activity.

Climate change is a global issue and will require concerted effort on the part of international organisations to reduce carbon emissions. However, to improve the recovery ability of reefs in the face of a changing climate, reduction of local impacts to reefs such as overfishing, land-based run-off and pollution is vital and models tell us that this can have a meaningful effect throughout the century. Reef managers have an increasingly important role to play in ensuring a future for coral reefs.



Juan Pablo Carricart-Ganivet

Universidad Autónoma de México

#### OUR RESEARCH

We are looking at the effect of temperature on rates of calcification in corals that form reefs.



*Basically we can highlight the importance of reefs in terms of the environmental services that they provide. At the global level we can talk about biodiversity as they are the ecosystems that support the greatest biodiversity in the ocean. 25 percent of the species that exist in the oceans live on reefs or somehow are related to coral reefs and the Caribbean is no exception. For many humans they are also relevant as a source of food, the protection of the coastal area, and well, in the Caribbean, tourism. If you think about it, it is very important as a source of foreign revenue for many countries. For example, in Mexico 20 percent of foreign currency comes in through areas with reefs, mainly Cancun.*

*I've seen so much change right in front of my eyes. 1980 was the first time I put my head underwater on a coral reef. I was an undergraduate student on a fieldtrip, studying for a career in biology and the teacher got my friend and me into the water. When I saw it, I said this is where I have to work. I have to devote myself to this. Where we entered, there were huge extensions of cervicornis and this was in Veracruz which has always had badly deteriorated reefs. The acroporas have practically disappeared. Montastraeas, the main reef builders, are in full decline. In terms of ecological importance we see a replacement of species. Acroporas and montastraeas are being replaced by porites and agaricias but the reef loses its core functionality with these species. I can say that what is now seen on the reefs in the Caribbean and in many parts of the world is a caricature of what it was when I first put my head underwater and if we keep going backwards, things only will get worse.*

In terms of ecological importance there is a replacement of species ...

1  
Factoring marine  
environments into  
resource management

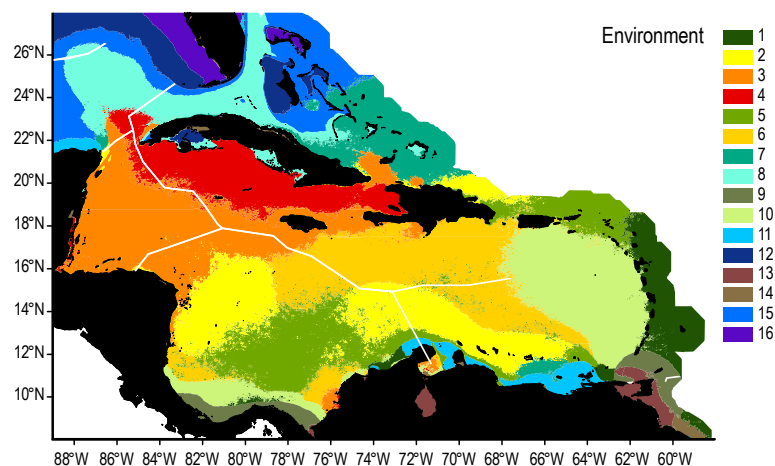


# Factoring marine environments into resource management

High wave energy environment.

## THE EVIDENCE

Many studies have looked at the physical environment and how it shapes the response of animals and plants. Some responses are very obvious, such as the impact of hurricanes damaging reefs and mangroves, or the effects of light on the availability of seagrass. Others are subtle, such as the differences in habitat types due to wave exposure from seagrass habitats found in very sheltered areas to reefs dominated by octocorals in exposed areas. At intermediate levels of wave exposure a larger diversity of habitats can coexist (e.g., seagrass beds and coral reefs). Wave exposure can also determine where major reefs are found. The most complex and biodiverse reef habitat in the Caribbean is built by large colonies of the mountainous star coral, *Orbicella* spp. and branching corals (*Acropora*) although the branching corals are now rare.



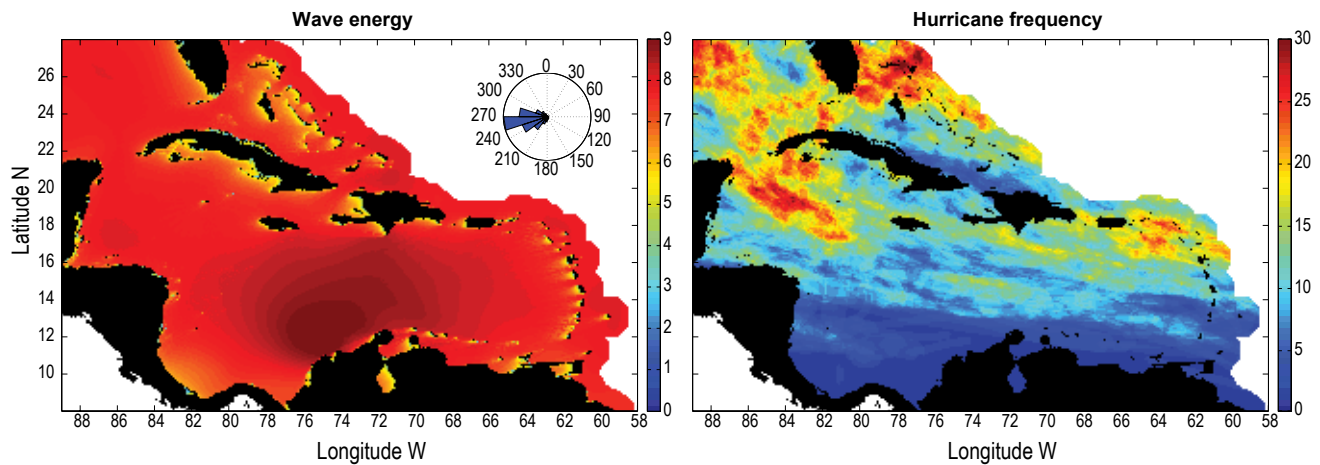
PECS classification of physicochemical regions. Each colour represents a distinct environment. White lines indicate the Marine Ecoregions of the World (Spalding et al. 2007, BioScience 57), previously the most detailed classification available for the area.

## THE ISSUE



*Marine ecosystems have long been exposed to the influence of diverse environmental forces such as extreme temperatures, upwelling, storms, river and runoff inputs, wave energy and hurricanes. These physical factors strongly influence reef biodiversity, the impact of disturbance, and recovery of marine ecosystems. However, data on physical environments have been difficult to acquire.*

*Recently, we used a wide range of satellite and field data to create the most detailed characterization of Caribbean environments to date. These maps, called Physical Environments of the Caribbean Sea (PECS), categorise the basin into distinct environmental provinces based on the characteristics of their waters at a spatial detail of 1 km<sup>2</sup>. As many organisms, particularly those living in shallow coastal habitats, are strongly influenced by mechanical forces of wave action and hurricanes, we also mapped average wave energy and the number of hurricanes that have impacted each site. These maps are available free online and will help managers plan their interventions and monitor their impacts.*



## MANAGEMENT IMPLICATIONS

By defining physical environments, PECS can be used for a variety of purposes within resource management:

- Mapping biodiversity proxies**  
 Good-quality data on marine biodiversity are scarce. Habitat maps are a common proxy for biodiversity assessments; however, they assume that species living in each habitat are the same everywhere. In reality, marine communities vary according to the physical environment even within a single habitat type. Habitat maps can now be stratified by physical environment to provide better proxies of biodiversity.
- Building ecologically representative marine protected area (MPA) networks**  
 The Convention on Biological Diversity emphasizes importance of including a representative range of diversity within an MPA network. A good way to do this is attempt to represent each habitat type in each of its physical environments.
- Assessing transferability of management approaches and setting realistic expectations for management outcomes**  
 Areas of the same environment are likely to respond similarly to management interventions (e.g., reserve impacts should be similar in comparable environments). PECS can help explain why some areas respond well to management and other areas (in different environments) respond differently.
- Setting priorities for rapid assessment/monitoring activities**  
 Stratifying field surveys by physical environment would facilitate a cost-effective, comprehensive appraisal of biodiversity within an area.
- Identifying potentially valuable or vulnerable marine ecosystems**  
 PECS can be used, for example, to identify areas where upwelling occurs, which might be particularly productive and valuable from a fisheries perspective. PECS can also identify areas under river influences, which might be heavily impacted by pollution.
- Mapping potential fishing access**  
 Areas with high wave energy tend to be too rough so receive less fishing.
- Mapping potential algal growth**  
 Much of the Caribbean has very weak tides and wind-driven waves play an important role in delivering fresh nutrients to algae which help them grow. Areas of high wave exposure tend to have faster-growing algae than sheltered areas. This information might identify areas that are more susceptible to algal overgrowth if herbivores are heavily depleted. Essentially, if parrotfish are removed, an algal bloom is more likely in exposed areas rather than in sheltered areas.

*PECS disturbance regimes, showing average wave energy (left, inset showing general wind patterns for the entire Caribbean) and hurricane incidence in the last 157 years (right).*

### FURTHER INFORMATION

[www.force-project.eu](http://www.force-project.eu) (freely available PECS maps via the FORCE webGIS)

Chollett I, Mumby PJ, Müller-Karger FE, Hu C. 2012. Physical environments of the Caribbean Sea. *Limnology and Oceanography* 57: 1233-1244.

# Coral Reef State and Resilience

*Corals have evolved and adapted over millions of years, having survived major changes in the Earth's climate and ocean circulation patterns. At the regional and local scale corals are impacted by natural events such as hurricanes and sediment outflows from rivers. Coral reefs can recover naturally from such impacts and this ability to recover towards a coral dominated state is termed reef resilience. Overfishing of herbivores, increased nutrient flows onto reefs from sewage and agricultural run-off, and the effects of climate change are all reducing reef resilience. On some Caribbean reefs, this has resulted in a change from reefs dominated by corals to reefs dominated by fleshy macroalgae. Such reefs do not provide the same quantity and quality of ecosystem services, such as coastal defence, tourism and fisheries, which millions of people are dependent upon. It is worthwhile prioritising the enhancement of reef resilience as part of any reef management programme.*



*Elkhorn coral on a shallow reef.*

## CORAL REEF STATE



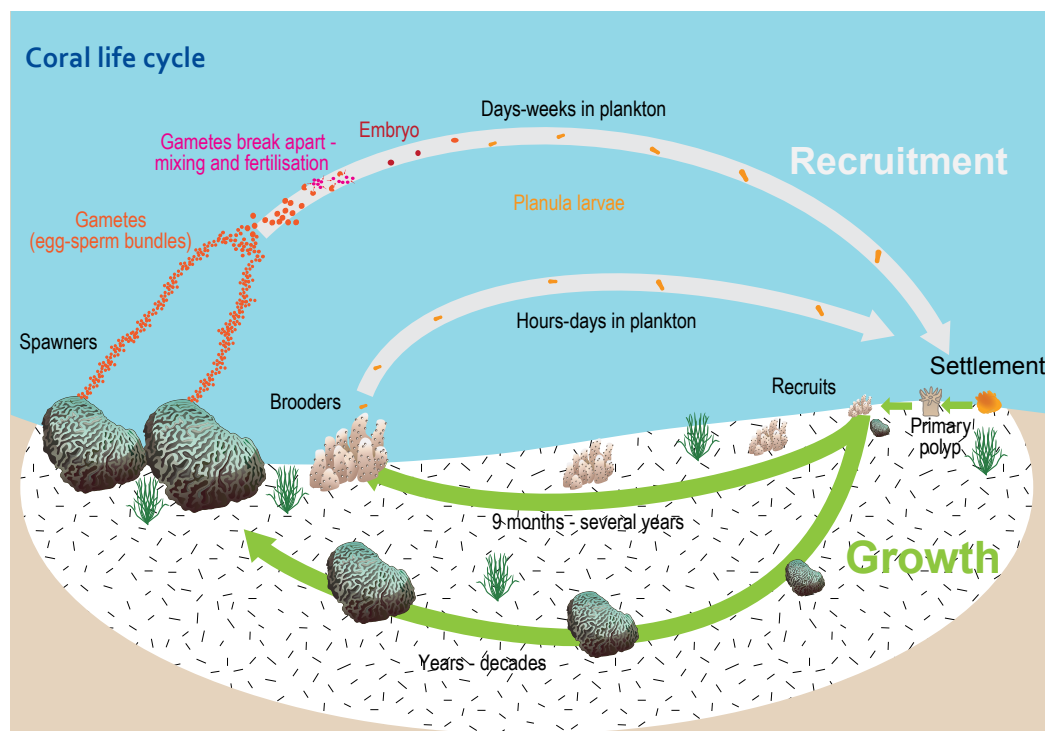
Juvenile corals at Karl's Hill dive site at Klein Bonaire.

Corals are constantly fighting for space with other sessile reef organisms such as algae and sponges. While these other organisms are also important to the reefs, maintaining the balance of competition in favour of corals is key to the maintenance of coral reefs (Chadwick & Morrow 2011).

Total coral cover on a reef is dependent on processes that affect the number of individual coral colonies (recruitment and whole colony mortality) and processes that affect their size (growth and partial mortality).

### Recruitment

Corals reproduce both sexually (with eggs and sperm) and asexually (cloning and fragmentation) (Baird et al. 2009). Sexual reproduction is in one of two modes: brooding or spawning. Brooding corals fertilise their eggs internally before releasing them into the water column as larvae (Baird et al. 2009). Spawning corals release unfertilised eggs and sperm into the water column where they mix and fertilise. In the Caribbean region, approximately 50% of coral species are spawners (Baird et al. 2009) and they constitute the majority of the reef building corals (Knowlton 2001). Both spawners and brooders can be hermaphroditic (i.e. corals can have both male and female functions, producing both eggs and sperm). Fertilised eggs, called planula larvae, drift in the plankton before settling onto a reef (Baird et al. 2009). The settlement of larvae onto the reef is triggered by several environmental factors such as the physical and biological surface structure of the substrate, light, water movement and even sound. Only a very small number of larvae will successfully settle and survive to form a new coral colony, a process called recruitment (Ritson-Williams et al. 2009). Once settled, the larvae turn into coral polyps (called 'primary polyp'). These primary polyps are highly vulnerable to environmental stressors such as algal overgrowth, predation and sedimentation. It is only after several months, when a coral colony is well developed, that mortality declines and recruitment occurs.



Schematic diagram of coral life cycle processes, showing some of the key differences between spawning corals and brooding corals. Mortality (not shown) occurs throughout the life cycle, though very high mortality occurs specifically during the recruitment process.



Thriving *Acropora* stand (left) and dead *Acropora* stand (right).

### Growth

Corals are able to extend their skeletons in different growth forms such as branching and encrusting (Done 2011). The colony growth process involves the division of individual coral polyps and the production of a calcium carbonate skeleton (coral calcification) (Done 2011). The calcium carbonate slowly accumulates over years and decades to form much of the three dimensional structure on coral reefs (Veron 2011). Most Caribbean corals have slow growth rates of less than 1 cm per year, the exception being the branching *Acropora* species, with *Acropora cervicornis* being the fastest growing at an average of 12 cm per year (Perry 2012).

### Mortality

In areas where corals are densely packed, corals will attack and kill each other as they fight for space (Chadwick & Morrow 2011). In the Caribbean this situation is now rare due to the low density of corals on most reefs today. Competition with algae and other sessile reef organisms such as sponges is much more common (McCook et al. 2001; Pawlik et al. 2013). Hurricanes can cause widespread, sudden mortality of corals (Gardner et al. 2005). These processes are natural causes of coral mortality. Mortality can involve the death of the whole coral colony or just part of the colony. However, mortality of corals worldwide

has been greatly increased over the last few decades by human impacts such as pollution and sediment from land-based run-off, overfishing and the effects of climate change (Hughes et al. 2003; Pandolfi et al. 2005; Mora 2008).

The processes of recruitment, growth and mortality are affected by many different factors such as the space available on the reef for new corals, competition between corals and other organisms, and disturbances, such as hurricanes (Table p.28).

It's clear that human activity has had almost uniquely negative effects on all three of the coral life cycle processes thereby reducing the coral cover on reefs and hindering the ability of corals to recover (Table p.28). Some of the anthropogenic drivers can act in synergy to produce a worse effect than they produce individually, e.g. corals are more susceptible to disease after bleaching events, so that the combined impacts of these two stressors can cause much higher coral mortality than the two separate impacts (Miller et al. 2006; Weil & Rogers 2011). Some impacts have long lasting effects, such as bleaching which reduces coral growth for several years after the bleaching event and also reduces coral reproductive ability (Baker et al. 2008).



Coral spawning.

## DRIVERS OF CHANGE IN CORAL LIFE CYCLE PROCESSES

Process	What affects the process?	Proximate effects on process	Anthropogenic influences on process	Resulting change in process (+ or -)*	References
RECRUITMENT	Substrate available for recruitment	Macroalgae and cyanobacteria hostile to larvae; some cryptic crustose coralline algae (CCA) aid coral settlement whereas others can inhibit settlement	Excess nutrients and overfishing of herbivores can increase abundance of macroalgae and cyanobacteria	—	(Arnold et al. 2010; Harrington et al. 2004)
	Predation and accidental mortality of coral recruits by grazers	Urchins and parrotfish in large numbers scrape coral recruits off substrate	<i>Diadema</i> urchin populations low due to disease, grazer numbers low due to overfishing	+	(Lessios 1988; Box & Mumby 2007; Burkepile & Hay 2009)
	Number of parent corals supplying larvae	Low numbers of corals result in fewer larvae	Increasing coral mortality due to human impacts	—	(Gilmour et al. 2013)
	Size of parent corals	Larger corals produce more larvae	Reduced growth due to human impacts	—	(see growth in this table)
	Fitness of parent corals	Stressed corals spawn less often	More frequent stresses, e.g. increasing coral bleaching events	—	(Mendes & Woodley 2002; Hoegh-Guldberg et al. 2007)
GROWTH	Substrate available for growth	Macroalgae and other sessile reef organisms compete with coral for space, often using chemical methods	Excess nutrients and overfishing of herbivores can increase abundance of macroalgae and other coral competitors	—	(Rasher & Hay 2010; Chadwick & Morrow 2011)
	Light	Reduced light reduces growth rate	Increased sediment from land use change (e.g. deforestation) blocks light from reaching corals	—	(Fabricius 2005)
	Sea surface temperature	Abnormally high or low temperatures can reduce growth rate	Climate change is increasing sea surface temperature	—	(De'ath et al. 2009; Carricart-Ganivet et al. 2013)
	Acidity of the oceans (pH)	More acidic oceans lead to lower calcification rates of corals, which can reduce growth rate	Increasing CO <sub>2</sub> in the atmosphere is increasing the acidity of the oceans	—	(Doney et al. 2009)
MORTALITY	Hurricanes	Large waves dislodge and shatter corals, and sediment can scour and bury corals	Climate change may be increasing intensity of hurricanes	—	(Rogers 1993; Mumby 1999)
	Coral bleaching	Prolonged high temperatures lead to coral mortality	Climate change increases the frequency and severity of bleaching events	—	(Baker et al. 2008)
	Competition	Macroalgae and other sessile reef organisms smother corals, causing partial mortality	Excess nutrients and overfishing of herbivores can increase abundance of macroalgae and other coral competitors	—	(Nugues & Bak 2006; Chadwick & Morrow 2011)
	Coral disease	Diseases infect and kill corals	Coral diseases are believed to be partly due to water pollution from e.g. sewage and agricultural run-off	—	(Weil & Rogers 2011)
	Bioerosion	Coral excavating sponges, urchins and other bioeroders erode coral structure, even destroy colonies	Excess nutrients, e.g. from sewage waters, favour the growth of bioeroders	—	(Hutchings 2011)

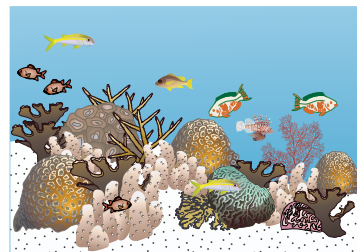
\* due to anthropogenic influences.

## PHASE SHIFTS AND REEF RESILIENCE

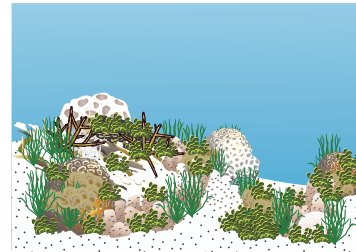
The global reduction in the abundance and size of corals has allowed other sessile reef organisms to occupy more space on the reef, resulting in community phase-shifts, where the dominant benthic community on the reef is no longer coral. Many of the recent changes on coral reefs have enabled macroalgae to expand, resulting in a shift to a macroalgal-dominated reef, a situation which is particularly common within the Caribbean today (Roff & Mumby 2012). Coral to algal phase shifts are typically triggered by sudden disturbances such as hurricanes and coral bleaching events (Mumby & Steneck 2008). One well-known, if not representative, example of a phase-shift is Jamaica, where coral cover on most reefs fell from approximately 50% in the 1970s to just 5% in the 1990s and the cover of algae rose from just a few percent to 90% (Hughes 1994).



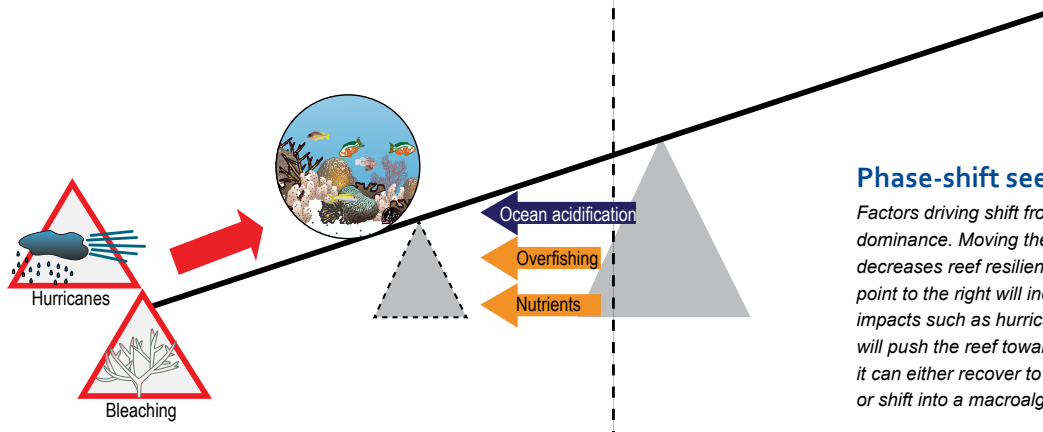
*Sudden disturbances can trigger a shift to an algal-dominated reef.*



**Coral dominated**



**Algal dominated**



### Phase-shift see-saw

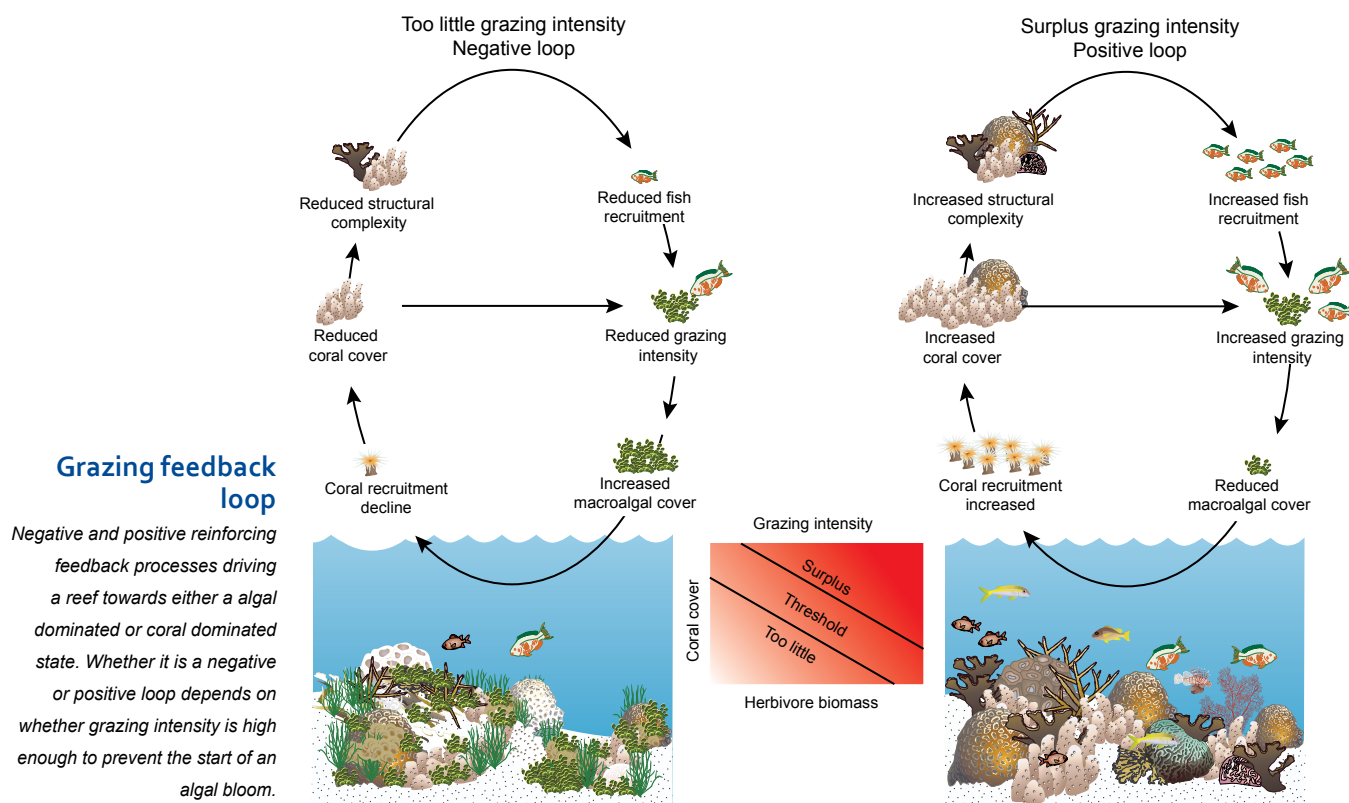
Factors driving shift from coral to macroalgal dominance. Moving the balance point to the left decreases reef resilience. Moving the balance point to the right will increase resilience. Acute impacts such as hurricanes and coral bleaching will push the reef towards the centre from which it can either recover to a coral dominated state or shift into a macroalgal-dominated state.



*Coral dominated reef.*



*Algal dominated reef.*



The trajectory of corals on a reef can either be one of recovery – if recruitment and growth outweigh mortality – or decline, where rates of background mortality outweigh recruitment and growth (Mumby et al. 2014). Here, the term 'background mortality' means the continuous mortality that occurs because of chronic processes like algal overgrowth, predation (corallivory), and potentially senescence. It does not include acute disturbances like bleaching or hurricanes. It is possible, therefore, that insufficient coral recruitment and growth will fail to sustain the coral population and coral cover will decline over time without any additional impacts of hurricanes and bleaching. A major cause of such declines is an increase in macroalgal cover or thick algal turfs (> 5 mm high) which vastly reduce the recruitment of corals (Arnold et al. 2010; Steneck et al. 2014). This means that adult corals are unlikely to be replaced when they die and that coral

cover will decline. The decline in cover will often lead to a reduction in grazing intensity that will allow macroalgae to increase further. As macroalgae continue to increase, coral recruitment declines even further, thus forming a reinforcing feedback that drives coral cover downwards (Mumby & Steneck 2008). This reinforcing feedback can also work in the opposite direction and increase coral cover if conditions are right. For example, if macroalgal cover is fairly low then coral recruitment is high and leads to an increase in the coral population size, and eventually to an increase in cover once the coral grows large enough. As coral cover increases, this tends to intensify the feeding of herbivorous fish into a smaller (non-coral) area and reduce algal cover further (Williams & Polunin 2001). The reduction in algal cover allows even higher levels of recruitment to occur, and so on.

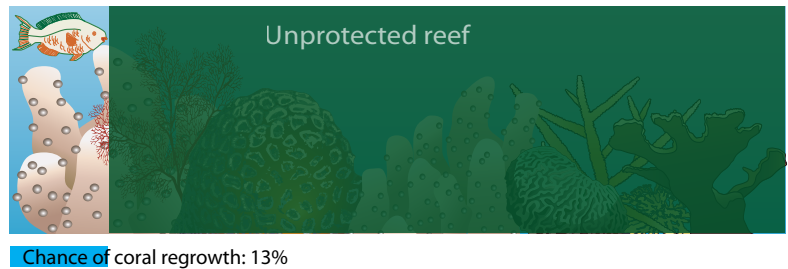
The key point here is that the local conditions on a reef can determine whether corals will exhibit a recovery trajectory or one of decline even in the absence of major disturbances (Mumby, et al. 2013). Clearly, it is important to avoid the trajectory of decline because this implies that coral cover will never be able to recover even after disturbances have ceased. Resilience is the probability that a reef will still be able to exhibit recovery trajectories after some defined period, of say 20-30 years, during which disturbances might increase (Mumby et al. 2014). A resilient reef does not necessarily have high coral cover or even coral dominance; it simply means that corals attempt to recover between successive disturbances. Essentially, the ecosystem still has the ability to heal itself!

Stoplight parrotfish (*Sparisoma viride*).



A major concern is that a combination of high algal cover (that slows recovery and growth) and episodic disturbance, such as bleaching (that reduces coral cover which favours algae), will drive the ecosystem across a tipping point where resilience is lost – i.e., where rates of coral recruitment and growth are unable to balance the background coral mortality.

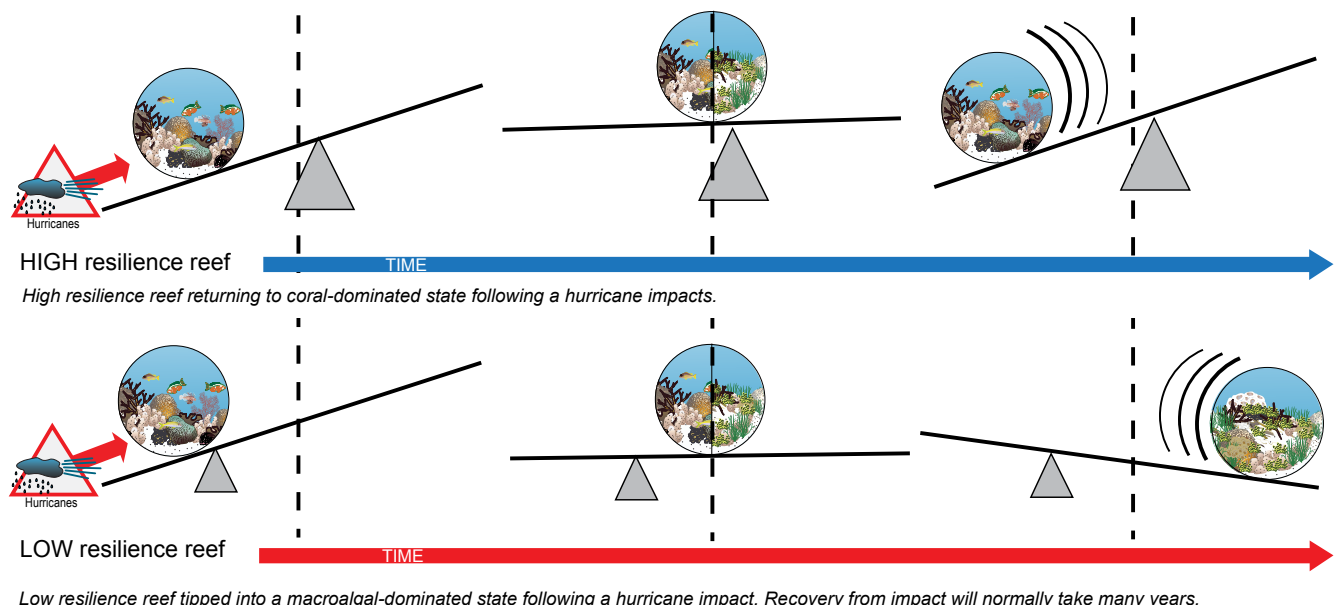
Recent research, using spatially-realistic ecological models, has allowed us to estimate the resilience of reefs in Belize and Mexico under projected climate change and natural levels of hurricane disturbance (Mumby, et al. 2014). Resilience was measured as the probability a simulated reef will recover within 100 year period following bleaching events and hurricanes. Two scenarios of greenhouse gas emissions were used (as adopted by the most recent IPCC report): 1) the optimistic RCP2.6 emission and concentration pathway, requiring aggressive global action to limit greenhouse gas emissions; 2) the most pessimistic RCP8.5 scenario, representing a 'business as usual' approach with little attempt to control emissions. These two emissions scenarios result in different coral bleaching impacts on the reefs, bleaching becoming most intense and frequent under RCP8.5. Under both RCP2.6 and RCP8.5, unprotected reefs in Belize were predicted to have low resilience by 2030. However, including the effect of protecting parrotfish in the model led to 6-fold increase in resilience in the same time period. Predictions for 2080 showed that resilience was 3-fold greater for RCP2.6 with parrotfish protection compared to the RCP8.5 scenario with no parrotfish protection. The important point for managers being that protection of parrotfish results in a large increase in reef resilience.



Bleaching affects the state of a reef by lowering coral cover, but it is predicted that climate change will also lower reef resilience by reducing the growth rate of corals due to increasing ocean temperatures and ocean acidification (Hoegh-Guldberg et al. 2007; Anthony et al. 2011). Specifically, a warmer ocean may lower the rate of growth of many corals giving reefs less opportunity to recover from more frequent and severe bleaching events (Baker et al. 2008; Bozec & Mumby 2014). Ocean acidification is also expected to lower coral growth rate (calcification) and therefore reduce resilience (Anthony et al. 2011). By reducing local stressors on reefs such as overfishing, pollution and land-based run-off, reef management can help re-build reef resilience and maintain the balance on reefs in favour of corals (Mumby & Steneck 2008).

*Corals are 6 times more likely to regrow after a disturbance when protected by a no-take reserve.*

### Hurricane impact on high and low resilience reefs



# LOSS OF REEF RESILIENCE IN THE CARIBBEAN

## Key events reducing reef resilience in the Caribbean:

### Loss of branching *Acropora* corals

These corals are important for reef resilience as they are the fastest growing corals in the Caribbean and they provide important structural habitat for fishes. Much of the *Acropora* cover was lost in the 1980s due to white-band disease.



### Loss of *Diadema* sea urchins

Along with parrotfish, *Diadema* are the key herbivores on Caribbean reefs. Mass die-off of *Diadema* due to disease has removed this important herbivore from many reefs, reducing the amount of algal grazing on the reefs.



### Chronic overfishing

This has reduced the abundance of herbivorous fish, principally parrotfish, which play an important role on reefs as grazers of algae.



## FURTHER INFORMATION

The Reef Resilience Toolkit provides more information and resources for managers: [www.reefresilience.org/](http://www.reefresilience.org/)

1  
Preventing blooms of  
cyanobacterial mats



2  
Reducing nutrients to  
restore the  
coral-algal balance



3  
Seagrass meadows as  
bioindicators of  
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4  
Influences of seasonality  
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5  
Thinking in 3D: integrating  
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6  
Conservation of  
parrotfishes to aid  
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7  
Bioerosion on coral reefs  
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8  
The use of sexual coral  
reproduction in reef  
restoration



# Preventing blooms of cyanobacterial mats

*Dense cyanobacterial mats.*

Recent research suggests that mats grow faster when exposed to higher levels of organic matter. Corals are adapted to life in a nutrient poor environment. Excess organic matter leads to the release of nutrients by microbial degradation, which stimulates the growth of cyanobacterial mats at the expense of corals. It is thus expected that measures decreasing the input of nutrients and organic matter on reefs will reduce the abundance of cyanobacterial mats and help to maintain reef health.

## THE EVIDENCE

Research along the coast of Curaçao compared the distribution of cyanobacterial mats with land usage and wave energy along the coastline. In the uninhabited south east part of the island, the mat abundance was very low (<1% cover), whereas it increased near industrialized and populated areas, especially close to estuaries (>30% cover). The only areas close to industrialized and populated areas where mats were less abundant were those exposed to high wave energy where nutrients are diluted faster and organic matter settles less on the seafloor. Sediments from sites with high abundance of mats were rich in organic matter compared to sites harboring few mats. Sediments are known to be a sink of organic matter. Researchers found that organic matter added to sediments can fuel the growth of cyanobacterial mats.

*Diver checking cyanobacteria.*

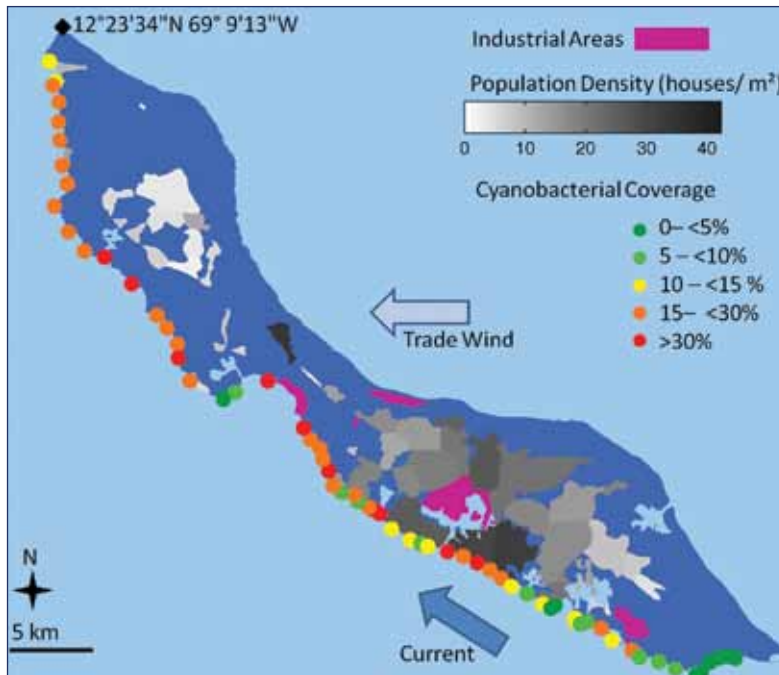
## THE ISSUE



*Cyanobacteria, also called blue-green algae, are a type of bacteria found in both aquatic and terrestrial environments. In the sea they occur as cells floating in the water column, as well as mats largely composed of intertwined cyanobacterial filaments covering the seafloor. On coral reefs cyanobacterial mats are normally rare. However, in recent years they have increased in abundance on many Caribbean reefs, sometimes reaching close to 50% cover in some areas.*

*Their increase can have a variety of negative consequences for the reef and the benefits that people derive from reefs. These go well beyond the simple loss of reef 'attractiveness' to divers. Cyanobacterial mats can grow quickly over the reef. They can prevent coral larvae from settling on reefs, can overgrow juvenile and adult corals and can act as coral pathogens.*

*Furthermore, they can produce chemicals which deter the grazing of fishes and urchins and have been linked to mass reef fish die-offs.*



Map of cyanobacteria coverage and human development on the island of Curaçao.

## MANAGEMENT IMPLICATIONS

High coverage of cyanobacterial mats on a reef indicates an increase in nutrients and organic matter which principally come from land-based run-off and pollution. Septic tanks, landfills and waste dumping areas leak nutrients into groundwater which can subsequently flow out onto reefs. Efforts could be made to reduce or stop untreated waste water and run-off from agricultural land reaching the reef.

Bays and other partially enclosed coastal areas have narrow or shallow openings towards the sea, naturally preventing nutrients from reaching the reefs. **Dredging and other activities that change water flow and increase flushing effects can lead to higher nutrient levels and, potentially, more cyanobacteria.**

Reducing nutrient inputs will not only reduce the abundance of cyanobacterial mats, it can also decrease the growth of macroalgae and bioeroders and slow down the spread of coral diseases.



Massive discharge of sediment loads by a river entering the Caribbean Sea off the Meso-American coast.

## FREQUENTLY ASKED QUESTIONS

### **Are cyanobacterial mats poisonous?**

Most cyanobacteria contain poisons. Blooms of cyanobacterial mats have been associated with mass mortalities of fishes. Direct contact may cause skin, eye and respiratory problems for humans.

### **Does anything feed on cyanobacteria?**

Cyanobacteria produce chemicals that fishes and urchins do not like to eat. There seems to be minimal grazing on cyanobacteria. A handful of small invertebrates are thought to feed on cyanobacterial mats.

### **Is there any economic value to be gained from cyanobacterial mats?**

None has been found so far.

### **Cyanobacterial mats come and go on coral reefs, so should we worry?**

Occasional mats are natural but an increase in their cover and frequency of occurrence could indicate a problem.



Cyanobacteria.

## FURTHER INFORMATION

Brocke et al. Organic matter degradation drives benthic cyanobacterial mat abundance on Caribbean coral reefs (in preparation).

# Reducing nutrients to restore the coral-algal balance

## THE ISSUE



Cyanobacteria overgrowing smooth flower coral (*Eusmilia fastigiata*).

### THE EVIDENCE

Researchers developed a new technique to determine which nutrient limits growth of macroalgae. Using this technique, the most abundant – and most damaging to coral – macroalgal species (*Lobophora variegata*) was found to be limited by the availability of nitrogen and phosphorus.

To examine which benthic organisms profit most from higher levels of nitrogen and phosphorus, coral, macroalgae, cyanobacteria and turf algae were exposed to nutrient pulses (raised levels of nutrients). Nutrients were delivered in the form of ammonium ( $\text{NH}_4$ ) and phosphate ( $\text{PO}_4$ ), both of which can be found in fertilizer and sewage. Macroalgae, cyanobacteria and turf algae were all able to take up nutrients much faster than corals. Turf algae took up nutrients faster than most macroalgal species.

Studies on turf algae and cyanobacteria showed that they can fix considerable amounts of molecular nitrogen ( $\text{N}_2$ ) under natural conditions and thus are less dependent upon external sources of nitrogen entering the reef. However, increases in external sources of both nitrogen and phosphorus can increase their growth rate as these nutrients often limit their growth under normal, low nutrient conditions.

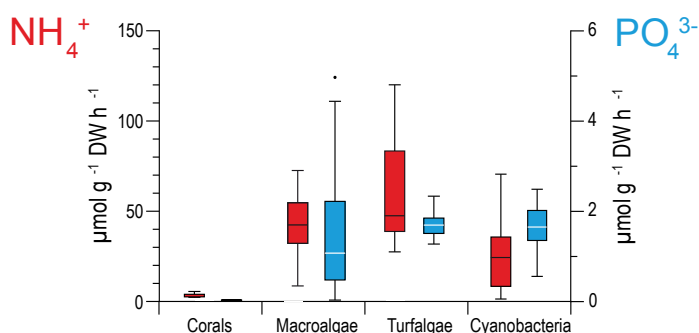
Close-up of turfalgae.

*On coral reefs, there is constant competition for space among benthic organisms such as corals, algae and cyanobacteria. Macroalgae are seaweeds that can overgrow neighbouring corals. Turf algae are diminutive mixed algal communities composed of small macroalgae and cyanobacteria. It has been shown that turf algae reduce the recruitment of new corals and can also overgrow existing corals. Cyanobacterial mats can overgrow both macroalgae and corals.*

*Recent human activities (e.g. coastal development and the use of fertiliser on agricultural land) have caused an unnaturally high flow of nutrients such as nitrogen and phosphorus onto many reefs. It is hypothesized that this causes macroalgae, turf algae and cyanobacteria to grow faster and overgrow corals. If nutrient influxes persist, coral reefs could turn into ecosystems dominated by algae and cyanobacteria, which decreases their ecological, economic and aesthetic value.*



Temporary nutrient enrichment events entering coral reefs from land as seen from the surface and under water.

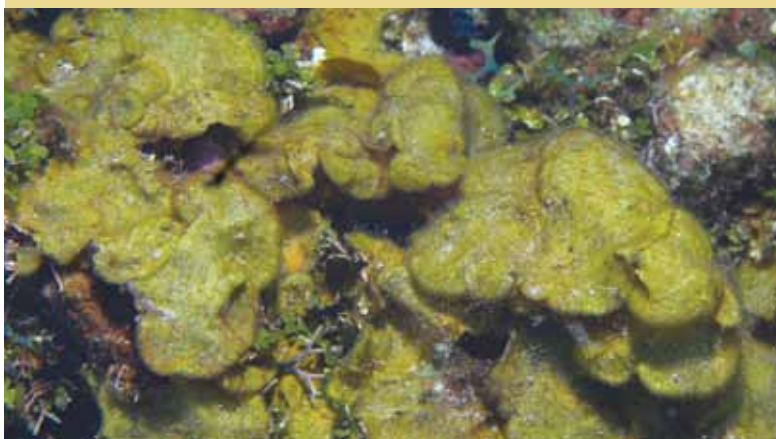


Ammonium and phosphate uptake rate per dry weight of corals, macroalgae, turfalgae and cyanobacteria.

## MANAGEMENT IMPLICATIONS

Reduce nutrient input to reefs, with a focus on sources of phosphate. Since macroalgae, turf algae and cyanobacteria all take up nutrients, reductions in nutrient flows onto reefs will help reduce the growth potential of these algae and cyanobacteria. Reducing the phosphate inflow will specifically decrease the growth of turf algae and cyanobacteria since they are less dependent on external nitrogen as they can fix otherwise unavailable nitrogen ( $\text{N}_2$ ). In particular, sources of phosphate, such as raw sewage outfalls, should be reduced.

Reducing nutrient flow onto reefs will ultimately benefit corals as they compete for space with algae and cyanobacteria.



Macroalgae (*Lobophora* sp.).

## FREQUENTLY ASKED QUESTIONS

### Can you tell me what nutrient levels are bad or good for my reef?

No. Nutrient levels can vary both in time (e.g. seasonal upwelling) and space (e.g. reefs near the mouth of a river are likely to have higher nutrient levels). However, if you continuously measure increased nutrient levels, efforts could be made to find and eliminate the source of the nutrients.

### Don't corals need nutrients too? Won't reducing nutrient levels on the reef harm the corals?

Corals do need nutrients, but they are naturally adapted to very low nutrient conditions (oligotrophic water). The growth of algae is limited by nutrients, so increases in nutrient levels tends to benefit them much more than corals, increasing their ability to outcompete corals for space on the reef.

### What are the major human sources of nutrients that flow onto reefs?

Sewage, fertilizers and untreated wastewater. These can come from many sources including, leaks from septic tanks, run-off from agricultural land and direct output of household wastewater into rivers and the ocean.

## FURTHER INFORMATION

den Haan J, Huisman J, Dekker F, ten Brinke JL, Ford AK, van Ooijen J, van Duyl FC, Vermeij MJA, Visser PM (2013) Fast detection of nutrient limitation in macroalgae and seagrass with nutrient-induced fluorescence. PLoS ONE 8(7):e68834.

Available free online: [www.plosone.org/](http://www.plosone.org/)

# Seagrass meadows as bioindicators of increases in nutrient levels

*Sparse seagrass meadow in the back-reef of the lagoon in Puerto Morelos.*

## THE EVIDENCE

Seagrass meadow communities consist not only of seagrasses but also of calcareous and non-calcareous (fleshy) algae, as well as other organisms. The composition of seagrass communities varies depending upon a number of factors including nutrients, light and the amount of disturbance at a site (e.g. waves).

The reef lagoon of Puerto Morelos in Mexico has been strongly affected by development in the surrounding tourist areas of Cancun and the Mexican Riviera Maya. Increases in nutrient levels, most likely coming from sewage output into the lagoon and increased land-based run-off, are visible as changes in the coastal seagrass meadows. In 1999, the seagrass meadow sites with greatest nutrient availability, due to their proximity to the town of Puerto Morelos and/or surface and underground water discharges, had either a greater biomass of seagrass or fleshy algae (principally *Lobophora variegata*). Fleshy algae had the greatest abundance at high nutrient availability sites with greater levels of disturbance (more exposure to sediment movement), as under such conditions the seagrass has larger shoot mortality and only algae take advantage of the high nutrient availability.

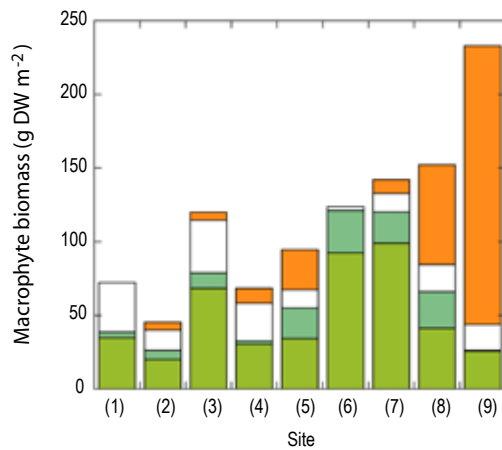
*View of the dense seagrass meadow located at the shore.*



*Coral reefs are naturally low nutrient environments. Corals are adapted to survive in such conditions, therefore large inputs of nutrients into the waters surrounding a reef can have negative effects on corals. It is normally algae that benefit from this nutrient enrichment, as relative to corals, they have higher growth rates and greater ability to take-up nutrients. This allows algae to overgrow parts of coral colonies and reduce the space available for the recruitment of new corals.*

*Detecting changes in nutrient levels on reefs is therefore key for managers so that they can reduce or remove sources of excess nutrients, hopefully before severe changes in the coral community become apparent.*

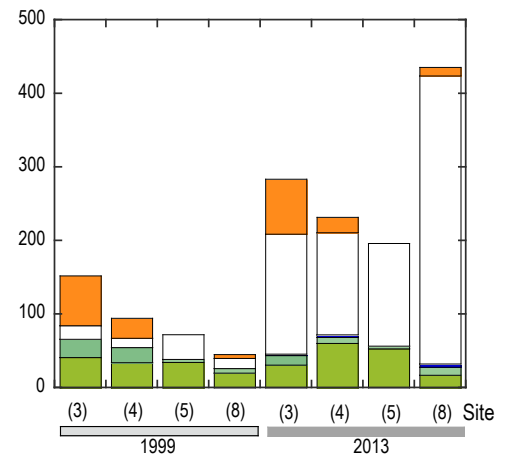
*Biological indicators (bioindicators) are used to assess the health of the environment and detect changes early, before damage to a habitat becomes irreversible. Seagrass meadows respond faster than corals to nutrient enrichment, and when they are located close to the reef, they act as a biological sink for nutrients, buffering the coral reef. Nutrient enrichment of seagrass meadows is visible as changes in the extent of the meadow and in community composition. These changes can be useful bioindicators, providing an early warning of nutrient enrichment in the water that may eventually impact the health of nearby reefs.*



Variation of the seagrass community (seagrass and algae) in the reef lagoon of Puerto Morelos. Sites closest to the town (6, 7, 8, 9) show either greater biomass of the seagrass *Thalassia testudinum* (6, 7) or of non-calcareous algae (8, 9; principally *Lobophora variegata*), in part due to greater nutrient availability.



- Non-calcareous algae
- Calcareous green algae
- *Halodule wrightii*
- *Syringodium filiforme*
- *Thalassia testudinum*



Changes over time in seagrass community composition at sites at the coast (3), in the lagoon (4) and in the back-reef meadows (5 and 8). Calcareous green algae show strong increases at all sites as they are heavier than the other parts of the seagrass community.

From 1999 to 2013 there has been a significant increase in the abundance of both calcareous and fleshy algae in the seagrass community. Since calcareous algae are much denser than both seagrass and macroalgae, they increased more as percentage weight of the community composition. Fleshy algae also increased in abundance at disturbed sites, whereas the seagrass *Thalassia testudinum* shows no increase at these sites. Although change in the seagrass biomass is not visible at some sites, the extent of the seagrass meadows has expanded over time and this can be seen in satellite images.



Calcareous algae: *Halimeda*.

#### FURTHER INFORMATION

Resilience Brief 2 p.36

Enríquez, S., and Pantoja-Reyes, N. I. 2005. Form-function analysis of the effect of canopy morphology on leaf self-shading in the seagrass *Thalassia testudinum*. *Oecologia* 145, 235-243.

van Tussenbroek B.I. 2011. Dynamics of seagrasses and associated algae in coral reef lagoons. *Hidrobiológica* 21 (3): 293-310.

## MANAGEMENT IMPLICATIONS

**There are three possible bioindicators in seagrass meadows of trophic changes in the coral reef habitat due to nutrient enrichment:**

- Increases in the abundance (cover and/or biomass density) of the dominant seagrass
- Increases in the presence of fleshy algae
- Increases in calcareous algae relative to the total mass of the seagrass community.

Changes should be significant and sustained, but will vary depending on the magnitude of the environmental disturbance, i.e. amount of nutrients being added to the water. Although large scale changes in the seagrass community can be seen on satellite or aerial photos, local monitoring of the seagrass meadow through measurement of shoot density, shoot size and leaf biomass of the dominant seagrass, provides a more sensitive method of detecting changes. Suitable data are collected in CARICOMP surveys which include measurements of seagrass biomass.

Importantly these bioindicators are helpful for detecting changes in the reef environment before serious impacts are observed in the coral community.

However, some care needs to be taken in interpreting environmental changes because cover and biomass of seagrasses and algae varies both spatially and seasonally and changes in the abundance of herbivores can also have a strong effect. Monitoring programs should therefore compare the same sites at the same times of the year (same seasons). Sites selected should aim to include the natural variability in conditions present in the area, but it is useful to include sites with low changes in sediment accretion and movement which are less prone to large changes in the seagrass meadow community. As seagrass meadow sites closest to the coast are the most disturbed ones, preferable sites for monitoring are closer to the reef community (i.e., back-reef).

## Influences of seasonality and herbivores on macroalgal growth



*Dictyota.*

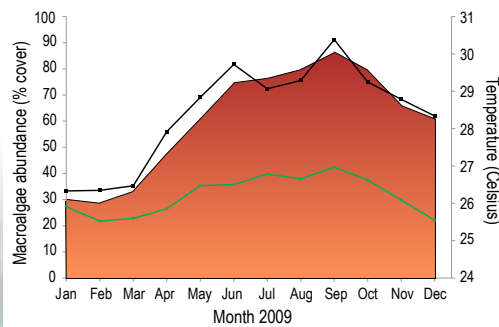
### THE APPROACH

To see the relative effects of herbivory and seasonality on algal abundance and growth, cages were used to enclose small areas of reef at Glovers Atoll in Belize. The cages excluded herbivorous fish and urchins from the reef area so that changes in algae could be investigated without the effects of grazing. Abundance of algae was compared between caged areas and non-caged areas over 13 months.

### THE EVIDENCE

Macroalgae grew to be twice as abundant in areas where herbivores were excluded (caged areas) compared to those where they were not. Seasonal change in macroalgae was clearly visible where herbivores were excluded, with a higher abundance of algae in the summer months with higher temperature and light levels. Seasonal variation was much more limited when herbivores were present. The abundance of individual species of macroalgae varied due to different factors.

Total macroalgae abundance in caged (black) and uncaged (green) areas; orange background shows temperature.

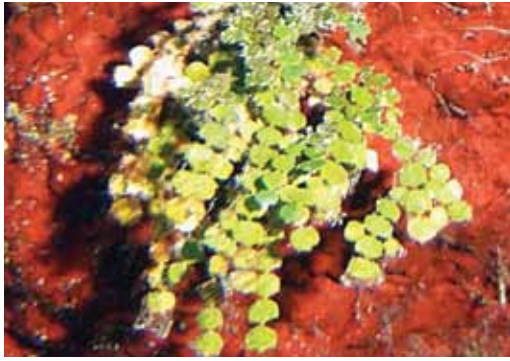


Macroalgae are a natural part of the reef community but on many Caribbean coral reefs they are becoming the dominant species as the cover of hard corals declines.

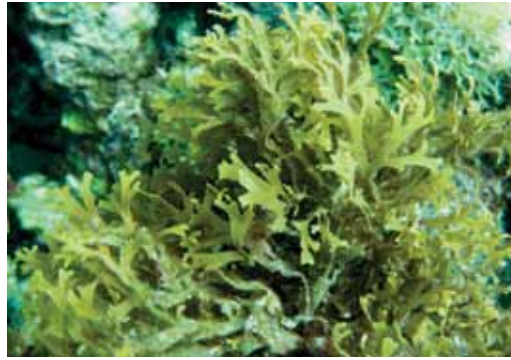
Macroalgae compete with corals for space and reduce the space available for juvenile corals to settle on the reef. Herbivores and nutrients are known to play an important role in controlling algal growth but changes in water temperature and light are also important. In most reef environments changes in temperature and light are mainly due to the change in seasons, i.e. lower light levels and temperature in the winter compared to the summer. Understanding the relative importance of seasonality and herbivory on the abundance of algae on reefs is important for managers who might be monitoring reefs at different times of the year and in areas with different levels of herbivory, e.g. inside and outside a marine park.

*Lobophora variegata*  
and *Halimeda*.

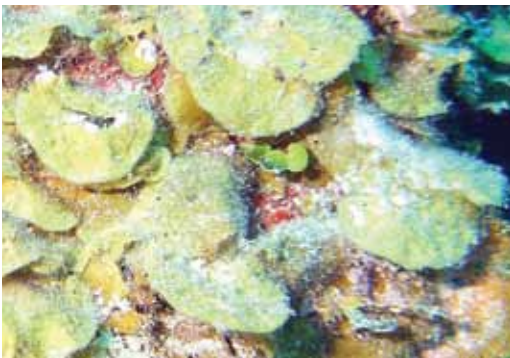
## Influences on abundance of algae



*Halimeda* spp. - abundance was reduced by the presence of herbivores.



*Dictyota pulchella* - only varied with seasonal changes; herbivores did not seem to control abundance.



*Lobophora variegata* - and algal turf abundances were reduced by herbivory but with no herbivores present, seasonal variations controlled abundance.



Overall, herbivores were found to play a strong role in reducing the abundance of algae, but changes in seasons (light and temperature) influenced which species of algae were most abundant.



## MANAGEMENT IMPLICATIONS

- **Consider the effect of seasonal changes in reef surveys.**  
Even on healthy reefs there are changes in the cover of macroalgae and the abundance of macroalgae species throughout the year. If reef surveys are conducted on the same reefs at more than one time during the year, managers should expect to see some variation in macroalgae, even if there are no disturbances (e.g. bleaching events, hurricanes) or other changes on the reef. To avoid the complicating factor of seasonal changes in macroalgae, it is best to compare data that was collected at the same time (month) each year.
- **Herbivores are an important control on macroalgae.**  
Without herbivores present, macroalgae can dominate the reef, squeezing out corals and reducing the chances of reefs recovering from disturbances such as hurricanes and bleaching events. Parrotfish are the main herbivore on most Caribbean reefs, though the *Diadema* sea urchin can be a very important herbivore if present in sufficient numbers (typically 1 or more per square metre).

It is advisable to protect both parrotfish and *Diadema* from overharvesting.

## FURTHER INFORMATION

Ferrari R, Gonzalez-Rivero M, Ortiz JC, Mumby PJ (2012) Interaction of herbivory and seasonality on the dynamics of Caribbean macroalgae Coral Reefs 31:683–692

# Thinking in 3D: integrating habitat complexity into reef management

Boulder star coral  
(*Orbicella*).

## THE EVIDENCE

Shallow reef underwater surveys in eight countries around the Caribbean revealed fish biomass and abundance was lower on flatter reefs than on complex reefs. Fish and coral species richness (the number of different types of fish or coral) were high even on medium complexity reefs, but were dramatically reduced on low complexity reefs. The major decline in fish species appears to occur when reefs transition from medium to low complexity. Parrotfish, snapper and grouper biomass also declined as reef structure is lost. Reef complexity is clearly an important component of coral reefs: with higher complexity supporting greater diversity, abundance and biomass of fishes, including fisheries target species (snappers, groupers) and ecologically important species (parrotfish).

Grunts and a squirrelfish  
under Elkhorn coral  
(*Acropora palmata*).

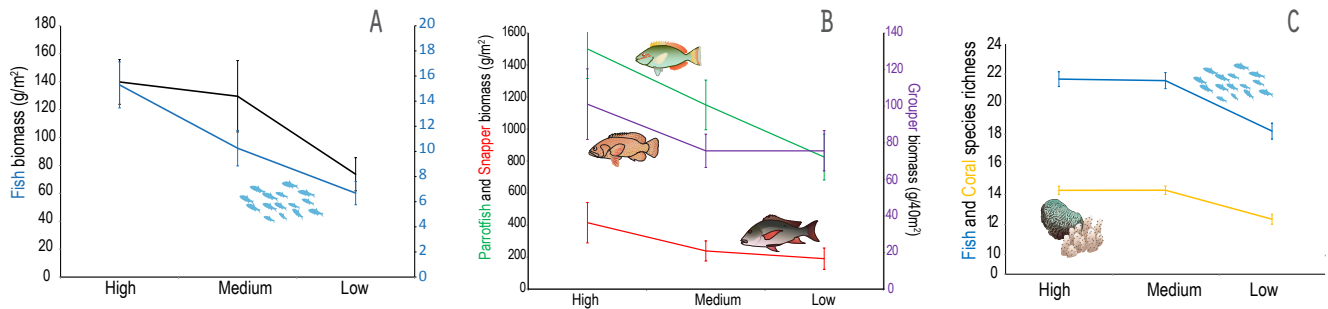
## THE ISSUE



*From rainforest to reefs, physical structure created by organisms (e.g. trees, corals) provides habitat for plants and animals. Structurally complex habitats support a greater diversity and abundance of life, resulting in healthier ecosystems which are typically more resilient to environmental change.*

*Coral reef habitat complexity is especially important for fishes, thus directly supporting valuable reef fisheries, diving and tourism.*

*Historically, complex physical structure has been provided on Caribbean reefs by large, branching staghorn and elkhorn corals (*Acropora cervicornis* and *A. palmata* respectively), but these corals have been in decline since the late 1970's. In their absence, reef structure has been maintained, to a large degree, by the boulder corals (*Orbicella*, previously *Montastraea* spp.). However, these corals are also under threat from disease outbreaks, bleaching events, sedimentation and the increasing intensity of storms and hurricanes. The loss of structurally important corals and the complexity they provide reduces the habitat available for reef fishes and hence their populations.*



Relationship between reef complexity and biomass (A and B) or species richness (C) (mean values with standard error).

## MANAGEMENT IMPLICATIONS

### • Protecting reef complexity

It is worth considering prioritising the protection of reefs with high and medium complexity. Management efforts could focus on human impacts such as sediment and nutrient run-off, overfishing and physical damage to the reef from anchoring and tourist activities.

### • Restoring habitat complexity

It is hard to create the naturally-occurring complex reef structure using artificial means so it is more cost-effective to prevent decline of existing habitat structure than attempt to restore it. The prevention of decline is achieved by managing the processes that drive coral reefs such as coral recruitment and growth. However, at small scales, reefs that have lost complexity may benefit from the addition of artificial structures to provide habitat and shelter for fish and help accelerate recovery. These reefs will need protection from fishing if long term recovery is to be achieved.

Introducing artificial structures into naturally low complexity reef areas creates habitat that was not necessarily there before: 'habitat creation', not 'habitat restoration'. Conditions for the development of corals are unlikely to be favourable (e.g. low-recruitment of new corals, high growth rates of macroalgae), limiting the long-term construction of natural complexity.

### • Measuring reef complexity

Reef monitoring protocols often use the chain method to quantitatively assess reef complexity, providing a useful measure of ecosystem health. Visual assessment of reefs using a simple 3 or 5 point qualitative scale can also be useful for categorising reefs for prioritisation in spatial management.

## FREQUENTLY ASKED QUESTIONS

### What if the coral is dead?

Dead coral can still provide habitat complexity but over time will become physically and biologically eroded. In the absence of coral recovery, a dead reef will lose its structural complexity and its function as a habitat for fish.

### Can artificial structures provide the same complexity as a natural reef?

Artificial structures will never be as good in a comprehensive ecosystem sense as natural reef structure. They are expensive and difficult to introduce on a large scale. Where artificial structures are to be used, it is important to consider that just as different corals provide different complexity and habitat (e.g. elkhorn coral versus boulder star coral), artificial structures can also provide different types of habitat and complexity.

### If I increase complexity on my reef, will fish come back immediately?

Yes, but initially this will be mainly fish drawn from surrounding reefs: The natural recovery of habitat complexity will typically take many years, but fish abundance will increase quickly in areas where artificial structure is placed, just as fish quickly colonize ship wrecks. However, this increased abundance may simply be fish drawn from the surrounding reefs, not new populations of fish.

## THREE POINT QUALITATIVE SCALE FOR MEASURING COMPLEXITY ON REEFS



# Conservation of parrotfishes to aid reef recovery

Queen parrotfish (*Scarus vetula*) feeding.

## THE EVIDENCE

A no-take marine reserve was established and actively enforced in the Bahamas. Parrotfishes are fished outside the reserve although most of the catch is accidental bycatch inside traps that are used to target snapper and grouper. Researchers monitored the recovery of corals at 10 sites, 4 of which were in the reserve, over a 2.5 year period. They found that the amount of algae was set by the number of parrotfish so that there was far less algae in the reserve where parrotfishes were large and plentiful. They also found that the recovery of corals was strongly related to the amount of algae. Corals showed positive recovery at sites with little algal cover but further degradation was found where algal cover was high. In short, the protection of parrotfish reversed the trend in corals from one of decline to recovery.

Stoplight parrotfish (*Sparisoma viride*).

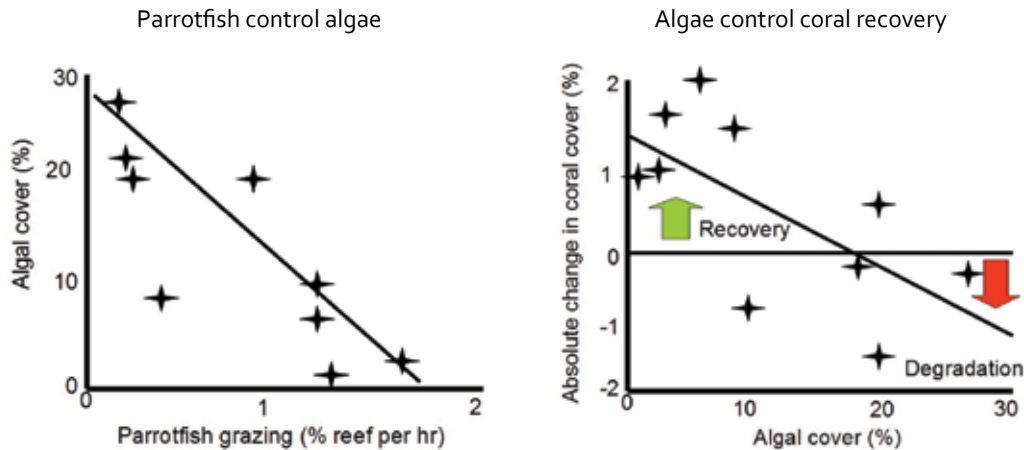
## THE ISSUE



*The coral on many Caribbean reefs is currently in a degraded state, often being below 10% cover whereas it should ideally exceed 40-50%. If corals remain in this degraded state for long periods of time then the benefits that people derive from reefs will be threatened. It is the corals that build the reef structure needed to provide habitat for reef fisheries, generate sand for beaches, and protect coastal areas from wave erosion.*

*There are many causes of this decline which include mass coral bleaching events, outbreaks of coral disease, hurricanes, mass regional decline of long-spined sea urchins, overfishing, and eutrophication. The precise causes will vary from place to place.*

*It has recently been shown that coral recovery can be helped by taking practical steps to manage parrotfishes. Parrotfishes are the main grazers of algae and high levels of parrotfishes are able to reduce the amount of algae on reefs. Algae can interfere with coral recovery in two ways. Firstly, by taking up space, algae prevent larval corals finding a place to settle on the reef and this effectively cuts off the supply of new corals. Secondly, algae smother established corals, which either stunts their growth or reduces their size.*



## MANAGEMENT IMPLICATIONS

### Policy Options

- **Most conservative**  
Draft legislation to outlaw the catch or selling of parrotfish as has been done in Belize. This policy may help sustain the long-term livelihoods of fishermen by helping to preserve the reef habitat needed by their target species.
- **Less conservative**  
Vastly reduce the use of fish traps which cause much parrotfish bycatch. Educate fishers to retrieve the traps regularly, haul them to the surface slowly, and return surviving parrotfishes.
- **Least conservative**  
Educate fishers to reduce their impact on parrotfishes and try to reduce fishing effort. The most important parrotfishes are the larger-bodied individuals. The most important species are the stoplight (*Sparisoma viride*), rainbow (*Scarus guacamaia*), queen (*Scarus vetula*), and princess (*Scarus taeniopterus*).

### Management expectations

Protecting parrotfishes will not return reefs back to their former, pristine states: there is simply too much stress on corals for a full recovery to take place in most locations. However, protecting parrotfishes is a concrete step that will help recovery and help stem the loss of reef services such as fisheries productivity.



Queen parrotfish (*Scarus vetula*).



Princess parrotfish (*Scarus taeniopterus*).



Stoplight parrotfish (*Sparisoma viride*).



Rainbow parrotfish (*Scarus guacamaia*).

## FREQUENTLY ASKED QUESTIONS

### *If my reefs still have lots of coral do I still need to bother?*

Yes. Experience has shown that coral cover can suddenly decline if the reef is struck by a hurricane, bleaching event, or disease outbreak. These events are unpredictable and recovery will be very slow or nonexistent if steps have not been taken to help natural processes of coral recovery.

### *There are lots of long-spined urchins on my reefs so are parrotfish still important?*

Yes. Urchin recovery has occurred in several parts of the Caribbean but it is usually limited to the shallowest few metres. Parrotfish remain the main grazer below this depth so the case for conservation remains.

### *People don't eat parrotfishes in my country so should I still consider these policies?*

Yes, it is ideal to implement these policies while popular resistance is low. Typically, parrotfish become targeted once more desirable fish species have been fished out. In Belize, for example, parrotfish harvest went from virtually unheard of to the most heavily-targeted species within a period of 10 years.

### *Are parrotfishes really good for reefs if they eat coral?*

It is true that some species of parrotfish take bites from live coral. However, all the evidence to date has shown that this impact is vastly outweighed by their positive impact in reducing algae. Corals suffer much more from algae than they do from parrotfishes.

## FURTHER INFORMATION

Mumby PJ, Harborne AR. 2010. Marine reserves enhance the recovery of corals on Caribbean reefs. PLOS One 5: e8657. Available free at [www.plosone.org](http://www.plosone.org)

# Bioerosion on coral reefs and monitoring its impact

Coral excavating sponge  
*Cliona delitrix* colonizing the coral *Siderastrea siderea*.

## THE EVIDENCE

The abundance of coral excavating sponges (the most important bioeroders in the Caribbean) is increasing on Caribbean coral reefs, particularly in the vicinity of sewage outlets and along eutrophication gradients. It is hypothesized that filter-feeding bioeroders such as molluscs and sponges benefit from an increase in the availability of new substrate due to coral declines and from surplus food in the water provided by sewage outflows.



Cross-section view of sponge excavation and infiltration of limestone rock.

## THE ISSUE



Bioerosion is the destruction and removal of substrate by the action of organisms. On coral reefs bioerosion plays a major role in the balance between constructive (calcification and cementation) and destructive forces (physical erosion, chemical dissolution and bioerosion). Bioeroders create suitable surfaces for corals to settle, increase habitat complexity and provide food for numerous reef-associated organisms enhancing biodiversity. Bioerosion is crucial for maintenance of coral reefs as long as it is in balance with calcification. Bioeroders create suitable surfaces for corals to settle, increase habitat complexity and provide food for numerous reef-associated organisms enhancing biodiversity. Bioerosion is crucial for maintenance of coral reefs as long as it is in balance with calcification.

This balance is now at stake. Coral reefs are declining worldwide and their calcification rates are being reduced due to factors such as eutrophication, coastal run-off and the effects of global warming and acidification. Worryingly, many bioeroders are less sensitive to these stressors than corals and are therefore colonizing newly available space on reefs. Bioeroders might even benefit from local and global anthropogenic disturbances. Consequently the balance is tipping in favour of bioerosion leading to a flattening of reefs and the loss of fisheries, biodiversity, and aesthetic beauty of coral reefs.



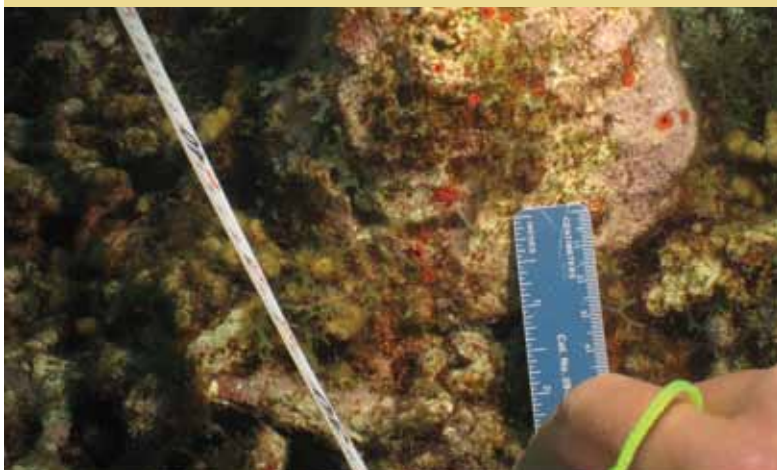
## MANAGEMENT IMPLICATIONS

Reducing waste water and land based run-off will help to reduce the supply of nutrients to the filter-feeding bioeroders. This will not immediately result in a change from net loss to net growth of reef structure but will help improve reef resilience.

To assess whether the reef is growing or losing structure, monitoring of bioerosion should be conducted. Several methods can be used to monitor bioerosion:

- Belt or line transects in which the cover and abundance of different functional groups of bioeroders is determined. The cover of bioeroding organisms (e.g. coral excavating sponges, sea urchins) is compared with that of benthic calcifying organisms (e.g. corals) giving an indication of the balance between calcifying and bioeroding organisms on the reef. The full methodology, including Excel data entry spreadsheets is available free online: [www.geography.exeter.ac.uk/reefbudget/](http://www.geography.exeter.ac.uk/reefbudget/)
- To assess relative differences in bioeroding organisms between sites, coral rubble and/or live coral colonies are collected and inspected for abundance, cover and composition of the bioeroding community and the abundance and size of the bore holes relative to the surface of the coral rubble piece.

The first method suggested can be integrated into existing reef monitoring protocols which measure benthic cover, e.g. AGRRA.



Measuring coral excavating sponge cover on a transect.

## FREQUENTLY ASKED QUESTIONS

### **What are the most common bioeroders on Caribbean reefs?**

Bioeroders can be categorized in two different groups: i) external bioeroders such as parrotfish, sea urchins and turtles that graze algae, sponges or coral tissue and as a by-product scrape off the surface of the limestone framework; ii) internal bioeroders which actively penetrate into the limestone substrate where they live permanently. The coral excavating sponges *Cliona delitrix* and *Siphonodictyon coralliphagum* can grow to become significant eroders of corals, destroying entire colonies.

### **How much limestone is removed by bioeroders?**

Some extremely destructive excavating sponges have been shown to be capable of removing limestone at rate of 30 kg/m<sup>2</sup>/year. Up to 40% of sediments in some regions of the Caribbean consist of sand grains produced by excavating sponges which are the dominant bioeroding organisms in this region.

### **Should we remove parrotfish and sea urchins from our reefs to reduce bioerosion?**

No! Despite the fact that sea urchins and parrotfish scrape off limestone when grazing for food, their negative impact as bioeroders is vastly outweighed by their positive impact in reducing algae and therefore promoting the growth of calcifying corals.

### **If bioerosion is an important natural process, why should we worry about it?**

Under relatively pristine conditions bioerosion increases habitat complexity, promotes species diversity and renewal of the benthic reef community and contributes substantially to sand production on coral reefs. However, anthropogenic disturbances such as eutrophication, overfishing and the effects of climate change directly or indirectly hamper coral growth and promote bioerosion, thus potentially leading to net loss of reef structure.

### **How is ocean acidification going to affect bioerosion?**

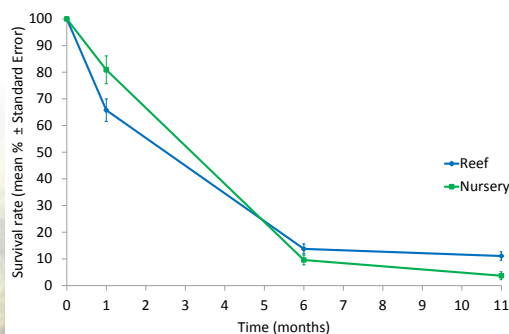
A lower pH due to ocean acidification is likely to increase bioerosion by facilitating the dissolution of limestone. At the same time these conditions hinder the calcification of framework-building corals. Both effects suggest a net loss of reef structure and stability due to ocean acidification in the future.

## The use of sexual coral reproduction in reef restoration

Staghorn coral  
(*Acropora cervicornis*).

It is currently not possible to restore complete reef ecosystems, therefore the most promising strategy is to focus on key species that will increase habitat complexity and stability, which can consequently lead to natural succession of other reef organisms. Elkhorn coral (*Acropora palmata*) and staghorn coral (*Acropora cervicornis*) are such key species that once dominated shallow reef habitats throughout the Caribbean. In the past decades, more than 90% of their populations have disappeared throughout their range mainly due to diseases and habitat destruction. Although both species still release their gametes (eggs and sperm) during annual mass spawning events, no significant recruitment has been observed in the Caribbean. Sexual reproduction represents a bottleneck in the life history of corals which needs specific attention in reef management efforts.

Survival rates of *Acropora palmata* settlers introduced to the reef as primary polyps (blue line) compared to settlers kept in land-based aquaria (green line).



Elkhorn coral  
(*Acropora palmata*).



Besides reducing local stresses on coral reefs from overfishing, sewage, coastal run-off and eutrophication, active reef restoration has recently become a popular management tool. In order to succeed in any effort, it is essential to realize that restoration is not an ultimate cure to stop reef degradation; however, when used in the right circumstances, it may support the natural reef recovery process. Restoration is only useful if the stressors causing degradation are significantly reduced or ideally eliminated before any restoration attempt is undertaken. In many cases, stress elimination alone will lead to successful recovery. However, if recovery is not expected to occur without active measures, restoration could be considered as a management option.

## THE EVIDENCE

Reef restoration projects can be expensive when land-based aquaria are used to grow the corals before being transplanted to the reef. Experiments in Curacao showed lower survival rates of elkhorn coral settlers kept in land-based aquaria compared to settlers that were directly outplanted on the reef after settlement. Furthermore the running costs of the aquarium, which could hold 4,000 settlement tiles was estimated at USD \$23,500 per annum.

Rather than using land-based aquaria, cheaper methods are to transfer recently settled corals: (1) directly onto the reef, or (2) into coral nurseries located on the sea floor, where the corals are kept several months before being outplanted on the reef. Whether Method (1) or (2) is applied depends on the conditions at the restoration site.

Method (1) works well for conditions with low algal growth and sedimentation at the restoration site. In the case study in Curacao, tiles with 10-15 elkhorn coral settlers were outplanted on the reef within 2 weeks of settlement. Although survival rates of settlers were relatively low, after 12 months 80% of the tiles had at least one surviving coral colony which recruited to the reef. Generally, the number of larvae is not the limiting factor

since several hundred thousand larvae may be obtained from one batch culture. Therefore, by increasing the number of settlers per tile, initial high mortality rates can be compensated and more successful recruitment achieved.

If conditions at the restoration site are less favorable and no settlers survive when using Method (1), Method (2) may be helpful. Initial settlers are temporarily transferred to an in situ nursery where potential negative effects (i.e. algal growth, sedimentation, and predation) can be more easily controlled. After 6-12 months, when settlers are large enough to be more resistant to algal overgrowth and other impacts, they can be outplanted to the reef.

## HOW IS IT DONE?

During annual mass spawning events, gametes (eggs and sperm) are collected from multiple colonies of the target coral species with either plankton nets with floats and/or collection cups. Within 30 minutes of collection, fertilization needs to be initiated on shore. Gametes of multiple colonies are put together in a highly concentrated suspension which turns slightly milky (approx.  $1-5 \times 10^6$  sperm cells  $\text{ml}^{-1}$ ). After one hour, all eggs are transferred to plastic bins with static fresh seawater (the sperm suspension is discarded). Depending on the quality of the gametes and the water conditions, fertilization



*Orbicella coral spawning.*



## FROM GAMETES TO RECRUITS

(A) Plankton nets are put above a spawning elkhorn coral to collect egg-sperm bundles in the plastic cups at top. A plastic-foam float keeps the nets in position. (B) Here, a regular cooler is used for batch fertilization. (C) The developing larvae are cultured for several days in flow-through devices to maintain high water quality. (D) Once settlement competent, larvae are transferred to bins with fresh seawater and pre-conditioned settlement tiles. The ceramic tiles have a diameter of approx. 7 cm (E) 6-month old elkhorn coral cultured in a land-based aquarium. (F) When outplanted on the reef directly after larvae settlement, settlement tiles may be fixed to rods which are fixed to the reef substrate using u-shaped stainless steel nails; Elkhorn coral, age: 12 months.

## TIME SERIES OF AN ELKHORN CORAL RECRUIT OUTPLANTED AT AN AGE OF ONE YEAR

1 week



2 months (scale bar = 1 cm)



6 months



12 months after outplanting



rates above 90% may be routinely reached. Unfertilized eggs deteriorate and reduce water quality, therefore high fertilization rates means better water quality and higher culture success. In addition, initial egg concentration (regardless whether fertilized) should not exceed 200 eggs l<sup>-1</sup>. However, if regular water changes are performed either by transferring the developing eggs twice per day to fresh seawater or by using flow-through culture devices, higher concentrations of 4,000-8,000 embryos l<sup>-1</sup> may be used. After 2-4 days, when larvae start actively crawling and swimming, settlement may be initiated by adding pre-conditioned settlement tiles, which have been exposed to natural seawater for several weeks to allow

growth of crustose coralline algae – a natural trigger for larvae settlement. When the majority of larvae have settled, disappearing from the water column, settlement tiles should be transferred to an in-water nursery close to the reef, or alternatively outplanted directly onto the reef. Land-based aquaria can also be used, though they are expensive and not as successful as the other methods (see 'evidence' p.49).

Studies are currently being carried out in Curacao and elsewhere to determine the long term survival of outplanted recruits as well as to optimize the developed techniques in terms of costs which are currently relatively high.

### REQUIREMENTS

**The use of sexual coral reproduction in restoration requires more knowledge and experience than other practices (i.e. fragmentation). Here are some logistical recommendations:**

- **Spawning times**

The precise spawning times of the target species have to be identified. They may vary between different geographical regions. Plan to dive more nights than just the predicted one since spawning dates may shift between years and on a local scale (between neighboring reefs)

- **Gamete collection**

- Target populations need to be easily and safely accessible by boat or from shore (night diving!).
- Although fertilization work can be carried out directly on the boat or at the beach, the culture facilities must be reached within two hours of fertilization being initiated to allow safe transfer of eggs to static culture bins.
- Collect from as many colonies as possible to enhance genetic diversity. Avoid sampling of neighbors. As a result of asexual fragmentation they might be identical genotypes.
- Work on a local scale. Do not use genetic material (gametes, larvae, settlers) from other regions (i.e. islands) to avoid the introduction of non-native genotypes.

- **Larvae culture**

Use low rather than high egg/embryo concentrations to avoid total collapse of the culture. It is best to use more culture bins to spread the eggs.

- **Model species**

Get a feeling for larvae behaviour, settlement and recruitment using brooding species which are much easier to work with compared to broadcast spawners. Ideal model species are the golfball coral (*Favia fragum*) and the low-relief lettuce coral (*Agaricia humilis*) which release larvae all year long and adult corals of these species can be easily kept in aquaria.

- **Outreach**

Coral spawning is a fascinating natural event. Make it a public event and invite locals to visit you at the culture facilities (not while working on the reef!). This helps raise awareness of reef conservation.

### FURTHER

### INFORMATION

SECORE Foundation

<http://www.secore.org/site/home.html>

Edwards, A.J. (ed.) (2010).

Reef rehabilitation manual.

Coral reef targeted research

& capacity building for

management program: St

Lucia, Australia. li + 166pp.

Download at: [www.gefcoral.org](http://www.gefcoral.org)



## Nancy Cabañillas-Terán

El Colegio de la Frontera Sur

### OUR RESEARCH

We are investigating how the rates of calcification have changed throughout the last decades. Using x-ray technology we look at the growth rings of reef-building corals to calculate the rates of expansion, density. We evaluate how the rate of calcification has changed in these reef builders and how these rates vary along the Caribbean, studying the aragonite saturation gradient.



*Coral reefs are very important because they offer tourist services which involve many actors. Mainly what we can see, for example, the white sand is produced by the calcium carbonate that formed in the reef. A large number of species is found there. Ultimately all fisheries depend on the reef.*

*For the past fourteen years I have had the opportunity to know the reef which is opposite to where I live and I have seen a big difference during this time. Before we could take a dive from the pier and there were corals from the reef lagoon, typical corals that are associated with the lagoon. We would swim out to the reef where there were a variety of breathtaking coral especially acroporas which are no longer there now. There are other areas of the reef to the South, which are in a little better condition. However I also have already seen a dead reef in front of the coast of Mahahual and it is quite sad. Yes, there has been a change, overall I would say, a lethal impact. Before there was nothing in the south now it is full of so many hotels that are not concerned about environmental standards.*

**... and we would swim up to the reef where there were a variety of breathtaking coral especially acroporas**



# Climate Change and its Effects on Caribbean Coral Reefs

*The effects of climate change are being felt across the world, with warming of the atmosphere, increases in sea level and reductions in the amounts of snow and ice. The oceans are changing too; not only are their temperatures rising, but ocean chemistry is changing due to increased amounts of carbon dioxide dissolving into the water resulting in ocean acidification. Both of these changes have important consequences for coral reefs. Higher ocean temperatures are linked to increased frequency of coral bleaching and increased prevalence of coral diseases. Ocean acidification will combine with elevated temperature to reduce the ability of corals to produce their calcium carbonate skeletons, which may lead to reefs that erode faster than they can accrete. Additionally, continued increases in the intensity of hurricanes in the Caribbean, linked to ocean warming, could hinder recovery of corals. Although the causes of climate change need to be tackled at a global level, this does not mean that local reef management is futile. Mitigating local stressors to reefs, such as overfishing of herbivores and sediment and nutrient run-off onto reefs, can greatly improve coral reef resilience in the face of climate change. A new method for factoring coral bleaching vulnerability into the design of MPA networks offers managers a further tool for planning for a changing climate.*



*Freighter enters Willemstad, Curacao.*

# GLOBAL CLIMATE CHANGE

The most recent report from the Intergovernmental Panel on Climate Change (IPCC) states that:

*"Warming of the climate system is unequivocal"... "The atmosphere and oceans have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased." (IPCC 2013)*

Globally, the average temperature of the Earth has increased by  $0.85^{\circ}\text{C}$  [ $0.65$  to  $1.06^{\circ}\text{C}$ ]<sup>1</sup> since 1880, though there is considerable geographic variability, with some areas warming more than others (IPCC 2013). In the Northern Hemisphere, it is likely<sup>2</sup> that the period 1983 – 2012 was the warmest 30-year period for the last 1400 years. Climate change has a big impact on the oceans as they have absorbed more than 90% of the energy put into the climate system since 1971 and approximately one-third of the carbon released by humans since 1750 (IPCC 2013; Khaliwala et al. 2013). This has led to a warming of the seas and an acidification of the oceans, corresponding to a decrease in pH (Graphs below).

Climate change is a concern for reef managers as the effects on the oceans are expected to make conditions increasingly difficult for corals (Table 1, p.55). The oceans have warmed fastest near the surface where coral reefs are located and continued warming is expected to result in an increased frequency of coral bleaching events and associated coral mortality (Frieler et al. 2012). Additionally, more acidic ocean conditions will reduce the ability of corals to produce their calcium carbonate skeletons (calcify) which is essential to forming the structure of reefs (Hoegh-Guldberg et al. 2007; Doney et al. 2009; Kroeker et al. 2013). This is likely to shift the carbonate balance of reefs ecosystems towards net erosion (Kleypas & Yates 2009; Andersson & Gledhill 2013). The impacts of climate change may be particularly negative for Caribbean corals which are already subject



Warming of the oceans will increase frequency and intensity of coral bleaching events.

to considerable stressors from anthropogenic impacts such as overfishing, pollution and land-based run-off from coastal development (Mora 2008).

## Monitoring climate change in the Caribbean

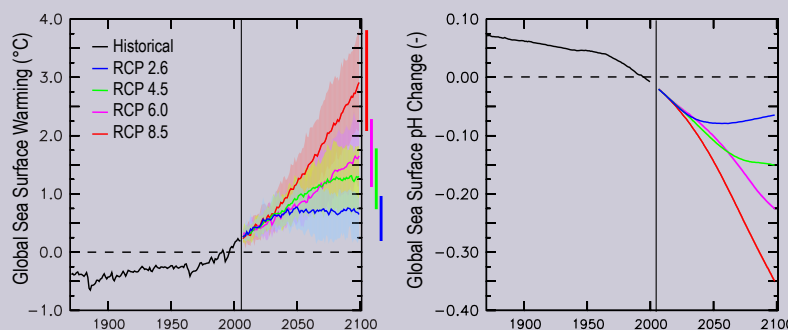
Considerable efforts are being made to model the future impacts of climate change on coral reefs and probabilistic maps of coral bleaching are now available through NOAA's Coral Reef Watch website: [www.coralreefwatch.noaa.gov/satellite/index.php](http://www.coralreefwatch.noaa.gov/satellite/index.php)

This website also provides extensive time-series data and near-real-time maps of sea surface temperature, ocean acidification, with other products such as coral disease risk prediction tools in development.

The Caribbean Community Climate Change Centre ([www.caribbeanclimate.bz/](http://www.caribbeanclimate.bz/)) provides climate change data for the Caribbean with high spatial detail (50 km). Included in the website is a regional climate modelling tool that allows users to extract and visualize data of predicted changes in temperature, precipitation, humidity and wind speed for the whole Caribbean region up until 2100.

## Modelled time series of global sea surface warming and pH change

Future projections use the four scenarios defined by the IPCC. RCP 2.6 represents an aggressive policy of greenhouse gas emissions reduction and RCP 8.5 represents a 'business-as-usual' scenario. RCP 4.5 and 6.0 represent scenarios in between these two extremes. Vertical line at 2005 shows the end of the historical simulation and start of climate change scenario models. Shading indicates one inter-modal standard deviation.



<sup>1</sup> The values reported in the square brackets represent the 90% confidence interval, i.e. there is a 90% likelihood that the value being estimated is covered by this range.

<sup>2</sup> The IPCC introduced a consistent terminology for the treatment of uncertainties in the observed patterns. A 'likely' event indicates more than 66% probability of occurrence.

## CLIMATE CHANGE EFFECTS ON CORALS

### Coral bleaching

Coral bleaching is the loss of the symbiotic zooxanthellae and/ or pigments that live within the coral tissue (Brown 1997). These zooxanthellae are vital to the existence of corals as they provide up to 95% of the energy requirements of the coral hosts (Hoegh-Guldberg 1999). Changes in salinity and light intensity can cause coral bleaching, but large scale bleaching events have only occurred due to anomalously high water temperatures (Eakin et al. 2010); an increase in water temperature of just 1 to 2 °C above normal maximum temperatures for 3 to 4 weeks being sufficient to induce bleaching (Hoegh-Guldberg et al. 2007).



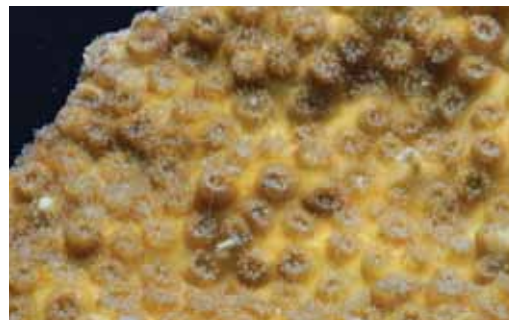
*Bleached porites coral.*



*Non-bleached porites.*

### Ocean acidification

As the concentration of CO<sub>2</sub> in the atmosphere has increased, the amount of dissolved CO<sub>2</sub> in the oceans has similarly increased. The absorption of carbon dioxide by the ocean triggers a series of chemical reactions which makes the oceans more acidic (lower pH) and decreases the concentration of carbonate in the water (Doney et al. 2009). Carbonate is vital to calcifying organisms, such as corals, which build their skeletons with calcium carbonate. Reduced availability of carbonate will place a further stress on corals, slowing their growth rate and resulting in structurally weaker reefs that erode more easily (Andersson & Gledhill 2013). In the most extreme case, very low pH conditions will result in the dissolution of coral skeletons (Fine & Tchernov 2007).



*The effects of extreme ocean acidification on a coral. A normal colony of the coral *Oculina patagonica* (top) and the same coral species after exposure to low-pH (pH = 7.4) conditions, showing the coral polyps exposed with no calcium carbonate skeleton. Global ocean pH is currently approximately 8.1 but could drop to below 7.8 by the end of century if no measures are taken to reduce greenhouse gas emissions (IPCC 2013).*

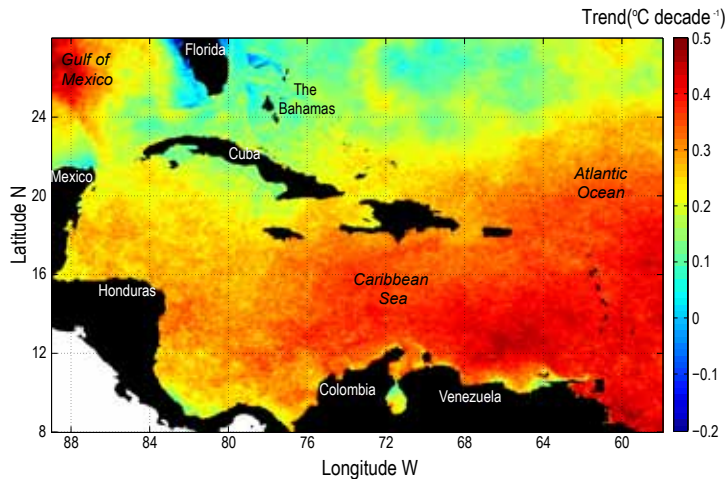


Negative effects of ocean acidification on other calcifying organisms, such as sea urchins, coralline algae and molluscs, are also expected, resulting in thinner shells and slower growth rates (Doney et al. 2009).

Climate change effect	Global observations (IPCC 2013)	Effect on corals	References
<b>Warming of the oceans</b>	Upper layer of the oceans has warmed by 0.11°C per decade over the last 40 years	Increased incidence of coral bleaching	(Donner et al. 2005)
		Reduced growth and reproduction rates	(Baker et al. 2008)
<b>Ocean acidification</b>	pH of the sea surface has decreased by 0.1 pH units since 1750	Less calcification – weaker skeletal structure and less reef-building	(Doney et al. 2009)
		Increase in bioerosion and dissolution of the reef framework	(Andersson & Gledhill 2013)
<b>Hurricane intensity increase</b>	Low confidence <sup>3</sup> in long term changes globally, but virtually certain in North Atlantic since 1970	More intense hurricanes cause more damage to corals	(Gardner et al. 2005)

<sup>3</sup>Low confidence indicates limited evidence to support the trend and poor agreement of datasets (IPCC terminology)

# CLIMATE CHANGE IMPACTS ON CARIBBEAN REEFS



Decadal warming trend for the wider Caribbean.

## Increasing sea-surface temperature

The Caribbean Sea has warmed on average by  $0.27^{\circ}\text{C}$  per decade over the period 1985 – 2009 (Chollett et al. 2012). This is a higher rate than the  $0.19^{\circ}\text{C}$  per decade ocean warming in the northern hemisphere over a similar period of time (Chollett et al. 2012). There are considerable differences in the temperature trends across the Caribbean region, with northern areas around Florida and the Bahamas actually showing some cooling, though the majority of the region has been warming with the greatest temperature increases in the south of the basin (Map above). Worryingly, most of the warming has been due to increases in summer rather than winter temperatures, which is likely to push organisms outside their ranges of thermal tolerance.

Higher temperatures are linked to the increasing frequency of coral bleaching events, with record high temperatures in 1998 and 2005 resulting in mass coral bleaching events (Wilkinson 2008). A further mass bleaching event in 2010 has yet to be well documented but is known to have caused coral mortality in some areas of the southern Caribbean, such as reefs in Colombia and Venezuela, which had escaped significant damage from previous bleaching events (Gaskill 2010; Bastidas et al. 2012; Bayraktarov et al. 2012). The stress experienced by corals due to bleaching

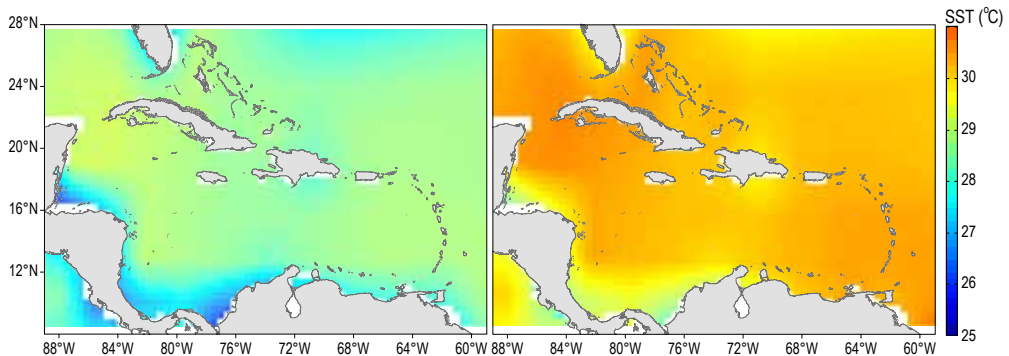
reduces reproduction rates and growth, thus reducing the recovery potential of bleached reefs (Baker et al. 2008).

Under a business-as-usual scenario of global carbon emissions, higher temperatures may make mass bleaching events like those of 1998, 2005 and 2010 biannual events within 20 – 30 years (Donner et al. 2007). However, some corals may be able to adapt and acclimate to increasing temperatures (Pandolfi et al. 2011) and some reefs experience much lower levels of warming than others, information that has been used to help improve the design of MPA networks (Mumby, Elliott, et al. 2011).

Increases in ocean temperatures are linked to outbreaks and increases in prevalence of coral diseases (Raymundo et al. 2008; Ruiz-Moreno et al. 2012). This is of particular concern for the Caribbean which is identified as a disease 'hotspot' due to the virulence, high prevalence, fast emergence and wide geographic spread of coral diseases in the region (Harvell et al. 2007). Disease outbreaks and increased spread of diseases following warmer ocean temperatures may be due to corals being less able to fight diseases when already stressed by high temperatures, or because the pathogens that cause disease are more virulent at higher temperatures (Raymundo et al. 2008). Poor water quality has also been linked to increases in the severity of coral diseases (Bruno et al. 2003), stressing the importance of local management actions that focus on reducing sediment and nutrients flows onto reefs and reduce pollution (Climate Change Brief 2 p.62).



White plague disease.



Decadal average summer sea-surface temperature in the Caribbean for 2020 - 2030 (left) and 2090 - 2100 (right). Data modelled using the IPCC-SRES B2 scenario, representing a less energy-intensive future with reduced carbon emissions.

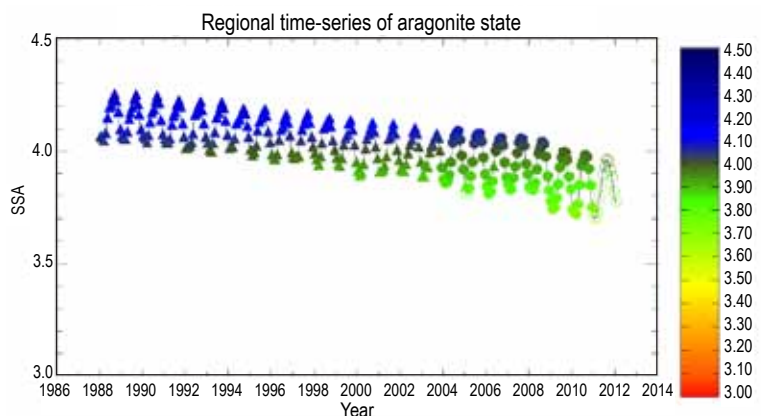
### Ocean acidification

The effects of ocean acidification on corals are not directly related to changes in pH per se, rather to changes in the aragonite saturation state of the water. Aragonite is the mineral form of calcium carbonate found in corals and some other marine organisms (Doney et al. 2009). The lower the aragonite saturation state of the water, the harder it is for corals to produce their skeletons. In the Caribbean, decreases in the pH of the sea have been accompanied by sustained decrease in aragonite saturation over the period 1988 – 2012 (Graph right; Gledhill et al. 2008). Patterns in aragonite saturation change spatially and seasonally in the basin, with higher values in summer and throughout the centre of the basin (Gledhill et al. 2008).

As of yet, there is little evidence of reduced coral calcification due to ocean acidification within the Caribbean, with a recent study on the Mesoamerican Barrier Reef finding no widespread effects (Carricart-Ganivet et al. 2012). However, as oceans continue to acidify with a predicted further fall in pH of 0.1 – 0.4 by the end of century (Graphs p.54; IPCC 2013), the impacts on coral reefs should become more detectable.

### Hurricanes and tropical storms

In the North Atlantic, the intensity of hurricanes has increased since the 1970s, and it is more likely than not that this trend will continue (Smith et al. 2010; IPCC 2013). Tropical storms and hurricanes are fuelled by warm seas, generally starting in areas where sea surface temperature exceeds 26°C (Emanuel 2003). Sea warming has contributed to a recent increase of 40% in



*Aragonite saturation state for the Caribbean region.*

hurricane activity in the tropical Atlantic between 1996 and 2005 (Saunders & Lea 2008). Storms and hurricanes can damage and remove corals from a reef through direct wave action, or cause indirect damage through abrasion by sediment and rubble and by depositing sediment which smothers the corals and blocks light. Stronger hurricanes cause more coral loss and within the Caribbean there is no evidence that reefs recover for at least 8 years post-impact (Gardner et al. 2005). However, hurricanes within the Caribbean have historically shown periods of high activity, followed by relatively quiet periods (Mumby, Vitolo, et al. 2011). This 'temporal clustering' of hurricanes is actually more beneficial for the health of reefs than random impacts as the first hurricane impact is more damaging than subsequent impacts that follow less than a decade later (Gardner et al. 2005; Mumby, Vitolo, et al. 2011). Hence, when reefs suffer repeated hurricanes over a short time period, the initial loss of coral may be large, but the following impacts have only a small effect on coral cover (Gardner et al. 2005).



## MANAGING FOR CLIMATE CHANGE

**Although reef managers can do little to directly reduce the greenhouse gas emissions that are causing climate change, there are some management actions that can help improve the future for coral reefs:**

- **Marine reserves designed for climate change.**  
Reef sites have different exposure to bleaching risk. Using satellite data on the temperatures reef areas are used to and how intensively they are impacted during extreme heating events, reef sites that are less likely to bleach or where corals are better prepared to cope with bleaching can be identified. This information can be used to aid in the design of marine reserve networks to maximize the probability of persistence of the entire network under a changing climate (Mumby, Elliott, et al. 2011).
- **Reduce local stressors on reefs.**  
Management actions such as decreasing land-based sources of nutrients and reducing herbivore overfishing can help improve reef health and increase reef resilience (Edwards et al. 2011; Kennedy et al. 2013). This will improve the ability of reefs to recover after bleaching events and hurricanes.



## Roberto Iglesias-Prieto

Universidad Autónoma de México



### OUR RESEARCH

is trying to understand the effect that temperature has on the aragonite saturation state and the rates at which corals calcify. The goal is the construction of a global model that will predict how the ability of corals to form reefs will change in the future.

*Coral reef ecosystems are not only the most iconic of the ecosystems but the services they provide to a community form a vital economic part of every one of the countries that make up the Caribbean. As food, as a main form of coastal protection and as a basis for tourism, people in the Caribbean are dependent on the services that the reefs provide. Diversity is very important for food security.*

*In my lifetime, I have witnessed really dramatic change on reefs. Sometimes it seems incredible considering that coral reef ecosystems have dominated as one of the most enduring of the tropical marine ecosystems. It is very alarming to think that in my short professional life I have witnessed dramatic changes on coral reefs: within the reefs right in front of my laboratory not only throughout the Caribbean. This is something that makes you think about what these ecosystems were like before the changes caused by human actions, not just global change but change in local land use and cultural change associated with tourism. The change has been quite dramatic.*

**People in the Caribbean are dependent on the services that the reefs provide**

1

Managing for climate  
change: incorporating  
bleaching vulnerability into  
MPA planning



2

Buying time for coral reefs  
by reducing local threats



# Managing for climate change: incorporating bleaching vulnerability into MPA planning

*Bleached Eusmilia fastigiata coral.*

## THE APPROACH

Maps showing vulnerability to bleaching can help manage reefs for climate change. The response of corals to temperature stress depends on the temperatures they are used to (preparedness or chronic stress) and the elevated temperatures they experience during extreme heating events (acute stress). Using this information, reefs can be classified into four categories based on their exposure to high temperature and the corals' preparedness: (A) those reefs accustomed to higher temperatures that have experienced relatively weak acute stress during bleaching, are expected to cope best with rising temperatures; (C) reefs with low preparedness but subjected to relatively weak bleaching stress should do reasonably but not as well as (A); (B) reefs that are prepared but suffer intense acute bleaching stress will likely fare worse than C; and (D) reefs with low preparedness that experience intense bleaching impacts will likely fare worst by climate change.

*Coral bleaching in La Bocana, Puerto Morelos, Mexico*



*Aerial view of cays in Los Roques, Venezuela.*

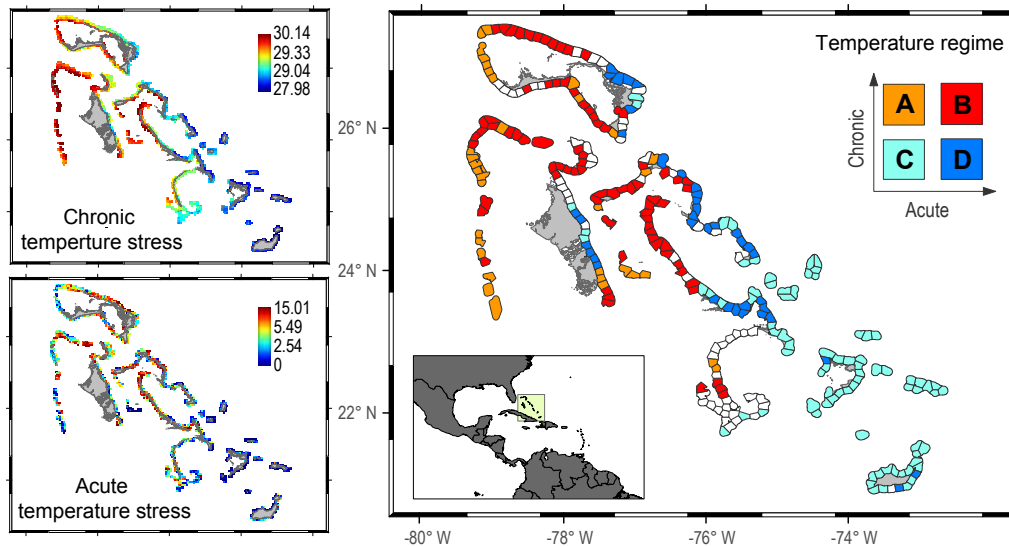
## THE ISSUE



*Coral bleaching, a stress condition in corals, happens when the algae that live in the coral's tissue, providing food and its normal healthy colour, are expelled. When bleached, corals starve, weaken and become more vulnerable to diseases and death. In some parts of the Caribbean, 80% of corals bleached and 40% died after the 2005 mass bleaching event. Since mass coral bleaching occurs when water temperatures increase, bleaching events will become more common and intense as the world's oceans become warmer.*

*In the long term it is clear that decreasing greenhouse gas emissions is the appropriate course of action to reduce the impacts of warming temperatures in corals. But what can we do at local levels?*

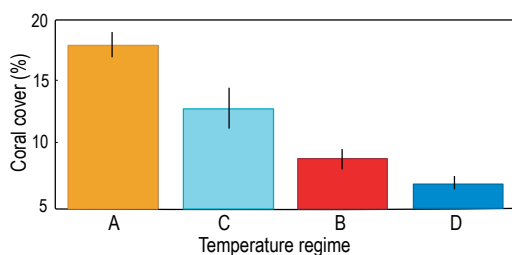
*When looking across reefs within a single country, there is large variability in where bleaching occurs. Reefs differ in their preparedness (acclimation) to bleaching and how intensively they are impacted by warming events. This variability can be harnessed by local managers by protecting reefs that are more prepared and have been less impacted by sea warming.*



Maps for the Bahamas showing chronic temperature stress; acute temperature stress for 1998 and temperature regimes.

## THE EVIDENCE

There is large spatial variability in chronic and acute temperature stress and bleaching incidence within the Caribbean which indicates that differences in bleaching vulnerability do exist. While the bleaching response has been related to the intensity of a warming event (acute stress), experimental studies have also shown that differences in preparedness or chronic stress also influence the response of corals to elevated temperature. For example, the pattern of coral cover in Belize after the 1998 bleaching event followed the combined effect of these factors, indicating that reefs under temperature regimes A and C are better suited to a climate change scenario.



Mean cover of living coral after the 1998 bleaching event in Belize, stratified by temperature stress regime.

## MANAGEMENT IMPLICATIONS

To maximize chances of success, we recommend managers focus protection on areas that are predicted to cope better with climate change (regimes A and C). If feasible, also including areas that offer the greatest potential for acclimation (regime B) could serve to hedge your bets. This information can be factored in with other relevant layers (e.g. habitat maps, maps of current uses) to prioritize conservation actions.

## HOW IS IT DONE?

Maps on thermal regime for selected locations across the globe can be found at <http://msel.abcgis.co.uk/tre/index.html>. If your area is not included there, thermal regimes can be identified using data freely available on sea surface temperature ([www.nodc.noaa.gov/SatelliteData/pathfinder4km/](http://www.nodc.noaa.gov/SatelliteData/pathfinder4km/)) and the methods outlined below. A full description of the methods is available in the manuscript referenced in the further information section.

The method's only input is sea surface temperature data. A measure of chronic stress is the average monthly summer temperature experienced over the entire data record available from satellites. The annual frequency of Degree Heating Weeks, a measure of accumulated temperature stress, is used as a measure of acute stress. When chronic and acute temperature stress have been quantified for each location within the area of interest, the measures are divided independently into three groups and locations at the extremes of each stress measure (i.e. upper and lower thirds) are used to generate the four contrasting temperature stress regimes. This method is based on historical data, therefore assumes that future incidence of bleaching events will be similar than past incidence. We currently are not able to predict future bleaching events at a fine, local scale relevant for management, but this approach provides a viable option to manage reefs for climate change.

## FURTHER INFORMATION

Bilko lesson on how to calculate thermal stress from satellite data:

[www.noc.soton.ac.uk/bilko/noaa\\_crw.php](http://www.noc.soton.ac.uk/bilko/noaa_crw.php)

Mumby PJ, Elliott IA, Eakin CM, Skirving W, Paris CB, Edwards HJ, Enríquez S, Iglesias-Prieto R, Cherubin LM, Stevens JR. 2011. Reserve design for uncertain responses of coral reefs to climate change. *Ecology Letters* 14: 132-140. Available at <http://dx.doi.org/10.1111/j.1461-0248.2010.01562.x>

## Buying time for coral reefs by reducing local threats

Local efforts on mangrove conservation.

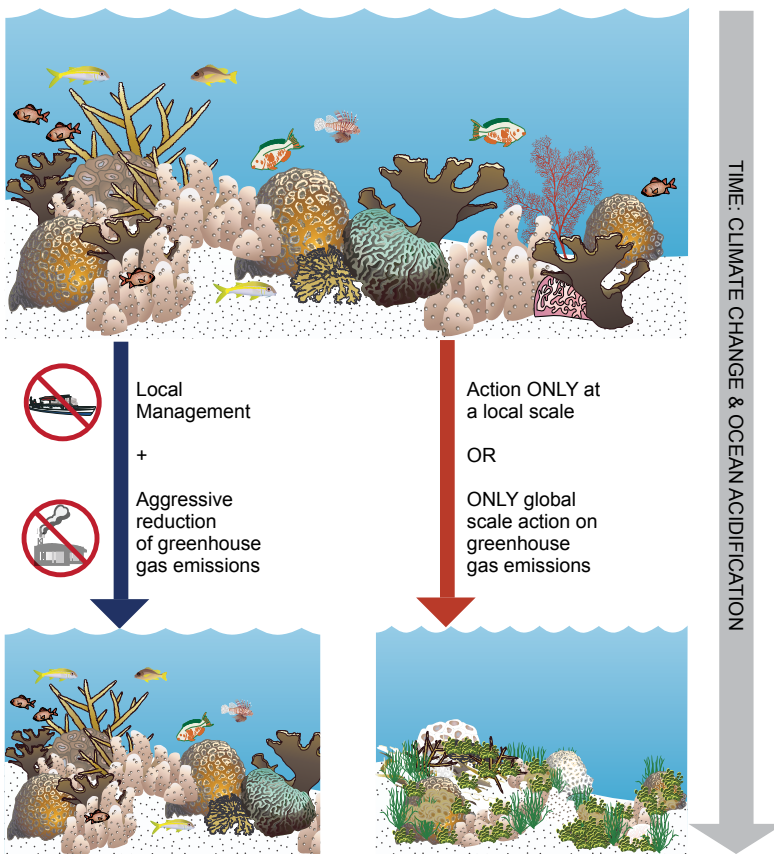
### THE EVIDENCE

A modelling study of Caribbean coral reefs examined the effects of different scenarios of climate change and local management on the net growth of reefs. Two climate change scenarios were examined: one 'business-as-usual', where little attempt is made to reduce global greenhouse gas emissions, and an alternative scenario of aggressive cuts in greenhouse gas emissions. Local management scenarios involved protecting herbivores and reducing nutrient run-off onto the reef. Results showed that only a combination of local management action and aggressive greenhouse gas reductions resulted in reefs continuing to grow in the future. In all other scenarios, reef growth began to decline before the end of the century. Coral cover of 10% may represent a threshold, below which reefs shift from net growth to net erosion.



Coral reefs provide ecosystem services, such as coastal protection, fisheries and tourism that are vital to the livelihoods of millions of people. These services are dependent upon healthy living corals and the structure they create. Corals generate skeletons of calcium carbonate (limestone) as they grow which provide a natural breakwater and the complex three dimensional habitat that is essential to support the high biodiversity of coral reefs. Other processes (e.g., cementation by coralline algae) also add to the growth of reef structure, while bioerosion helps further create complexity and is essential in determining the balance between reef growth and disintegration.

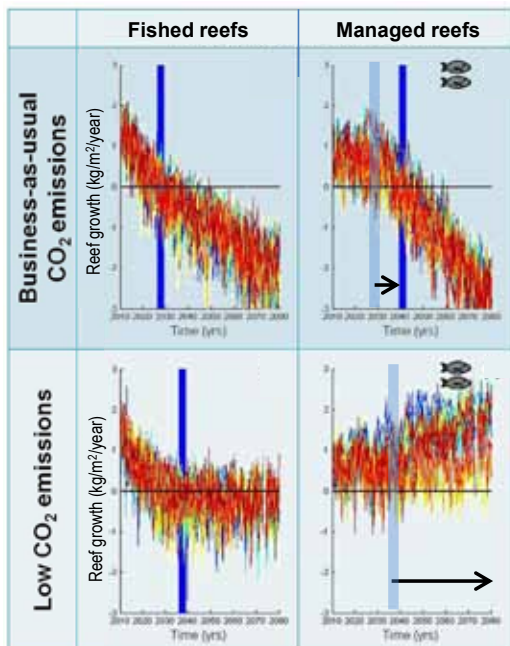
Climate change is expected to reduce the ability of corals to form reef structure. Rising ocean temperatures are projected to disrupt growth rates for many corals and increase the frequency of coral bleaching. Ocean acidification will also slow coral growth and weaken reefs, at the same time as increasing the rate of bioerosion. In the face of such impacts, local efforts to improve reef health might seem hopeless. However, recent research has shown that local management of reefs is vital to maintain the continued net production of reef structure, and therefore the provision of the important ecosystem services that reefs provide.



Both local management of reefs and global action to lower greenhouse gas emissions are needed to maintain structurally complex reefs and the important services they provide.

## Caribbean reef growth

Caribbean reef growth (in terms of kg's of limestone generated per m<sup>2</sup> of reef area per year) simulated until 2080. Under 'Business as usual' climate scenarios (top panels), all 20 simulated reefs went from growing at 1-2 kg/year in 2010, to eroding by 3 kg/year by 2080. However, the point at which reefs stopped growing (dark blue line) was delayed when reefs were locally managed to protect herbivorous fish and improve water quality. Where action was taken to limit GHG emissions (bottom panels), only managed reefs were able to maintain their growth rates until 2080.



→ Time bought by management  
 ■ Threshold at which erosion exceeds growth in most reefs



## MANAGEMENT IMPLICATIONS

### Effective local management is essential

Protection of herbivores is vital for reefs to withstand predicted impacts of climate change. Although global action to reduce greenhouse gas emissions is essential to ease the effects of climate change on reefs, such efforts are not sufficient on their own to ensure reefs continue to exhibit net production of three dimensional structure.

Unprotected reefs will degrade quickly due to reduced coral growth and cover, and increased bioerosion. Although improved local management measures alone may not be sufficient to ensure continued growth of reef structure, such measures are vital for buying time for reefs while global action on climate change is negotiated. Local management efforts that protect herbivores and reduce nutrient run-off onto reefs will maximise the chances that healthy reefs and the services they provide are maintained in the future.

## FURTHER INFORMATION

Resilience Brief 5 p.42, Brief 6 p.44, Brief 7 p.46

Kennedy EV et al. 2013. Avoiding Coral Reef Functional Collapse Requires Local and Global Action. *Current Biology* 23 (10): 912 – 918.



Dredging and landfill activities can increase sediment loads and nutrient levels on reefs.

# Coral Reef Fisheries Management



Caribbean reef fisheries are a vital source of income and food for thousands of people in the region, with annual net benefits estimated at US \$395 million. Reef fisheries also provide an important social safety-net for people when other sources of employment are unavailable. Populations of reef fishes and other important fishery species such as queen conch (*Strombus gigas*) and spiny lobster (*Panulirus argus*) have been severely reduced across the region due to a combination of overfishing and habitat degradation. Management of coral reef fisheries has to take into account the diverse nature of the fishery including factors such as multiple species harvested with multiple different gears, geographically dispersed fishing and landing sites and the variable nature of the fishers' dependency on the fishery. Resources available for the monitoring and control of coral reef fisheries are often limited, but good management is vital for ensuring the long-term viability of the fisheries. Ecosystem-based fisheries management (EBFM) is suggested as a better alternative to conventional fisheries management practices and is particularly appropriate for coral reef fisheries. The focus is on maintaining the health of the coral reef to ensure sustainable fishery yields and other critical ecosystem services of reefs. EBFM is being promoted throughout the region and new tools are being developed to help managers introduce EBFM measures. Existing fisheries management tools, such as no-take areas and catch quotas, will continue to be used alongside new and improved tools, such as habitat protection zones and vessel monitoring systems (VMS), which will expand the range of fisheries management measures available. Only by understanding and managing the effects of fishing as well as other impacts on the ecosystem can managers ensure sustainable use of coral reef fisheries.



Parrotfish catch.

## CARIBBEAN REEF FISHERIES FROM PAST TO PRESENT

*"Generally, a fishery is an activity leading to harvesting of fish. It may involve capture of wild fish or raising of fish through aquaculture."*



Queen conch.

Caribbean reef fisheries have been an important source of food for coastal communities since at least 200 B.C. (Wing & Wing 2001). Today they not only provide food but valuable income and employment opportunities with annual net benefits from Caribbean coral reef fisheries estimated at US\$ 395 million and approximately 300,000 people employed in the Caribbean fisheries sector as a whole (Agard et al. 2007; Burke et al. 2011). Caribbean spiny lobster (*Panulirus argus*) and queen conch (*Strombus gigas*) are two of the most highly valued reef-related species in the region, with the Caribbean lobster fishery alone estimated to be worth US\$ 456 million a year (Ehrhardt 2005).

Most reef fisheries within the region are small-scale artisanal fisheries, with large scale industrial reef fishing limited to a few conch and lobster fisheries. While revenues from reef fishing make up only a small proportion of the GDP of most countries within the region, the reef fishery is easy to access and serves as a food and employment safety-net for coastal communities in hard economic times or following natural disasters (Pauly 2006; Béné et al. 2010). Livelihoods research conducted by the FORCE project found households in St Kitts and Nevis as well as Honduras depended heavily on coral reef fisheries after losing their jobs in other economic areas such as construction work (Livelihoods Brief 2 p.142). This safety-net function of the reef-fishery may be particularly important in Caribbean nations, many of which have limited social security schemes and are highly dependent on the seasonal and volatile tourism sector.

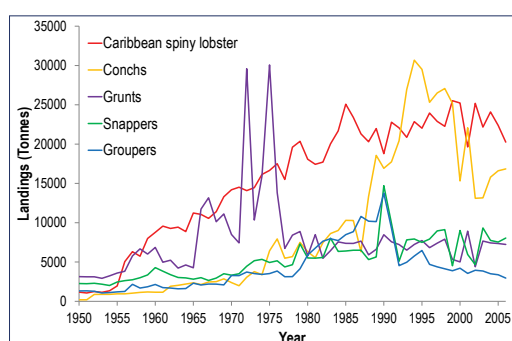
The dual economic and social value of reef fisheries makes the declining state of Caribbean coral reefs (Gardner et al. 2003; Jackson et al. 2012) and fish stocks they support (Paddock et al. 2009) a matter of serious concern. Overfishing is a pervasive problem in Caribbean reef fisheries which are typically open-access (i.e. the right to catch fish is free and open to all). Archaeological evidence suggests reef fish stocks were heavily exploited by the Amerindian population in the



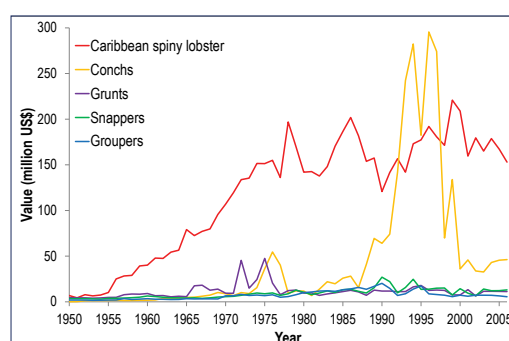
Reef fish catch being sorted at a dock in Honduras.

region (Wing & Wing 2001) and subsequently by colonial settlers after the arrival of Columbus, such that recent declines are only a continuation of a centuries old pattern (Jackson 1997; *Biogeography* p.13).

Although there is considerable variability in Caribbean reef fishery data, landings of most species have been stable or declining since the 1980s (Graph below left). This is despite increased fishing effort in terms of both improved gear and more fishers. High demand for many reef species from both local and export markets has driven increasing prices which has led to overexploitation, particularly of queen conch and Caribbean spiny lobster which are among the highest value species (Graph below right; Appeldoorn et al. 2011; Ehrhardt et al. 2011). The ease of access to the reef and the life history traits of many reef fishery species make them particularly susceptible to overfishing (Sadovy 2005). As a result, some of the most vulnerable and desirable reef-fishery species are now recognized as endangered.



Landings of main Caribbean reef fishery species.



Catch value of main Caribbean reef fishery species.

Examples include those listed on the IUCN red list ([www.iucnredlist.org](http://www.iucnredlist.org)) as:

- critically endangered – Atlantic goliath grouper (*Epinephelus itajara*), Warsaw grouper (*Hyporhamphus nigritus*), hawksbill turtle (*Eretmochelys imbricata*);
- endangered – Nassau grouper (*Epinephelus striatus*);
- vulnerable – hogfish (*Lachnolaimus maximus*), mutton snapper (*Lutjanus analis*), yellowmouth grouper (*Mycteroperca interstitialis*).

Most species of shark, now almost absent on Caribbean reefs despite historical evidence that they were once commonly sighted in large numbers (Ward-Paige et al. 2010), are also listed as vulnerable by the IUCN red list. Queen conch is listed in Appendix II of CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) in recognition that the resource is under threat from international trade. Queen conch is also listed in Appendix III of the SPAW (Specially Protected Areas and Wildlife) protocol of the Cartagena convention in recognition of the need to protect critical habitat and ensure sustainable use (Vallès & Oxenford 2012) and is currently under consideration for listing in the US Endangered Species Act.

Serious environmental and socio-economic impacts of overexploitation on reefs include:

- Reduced abundance of stocks resulting in decreased total catches, lower catch per unit effort, reduced food security and reduced livelihood opportunities (Services, Brief 2 p.110).
- Change in trophic structure of fish populations (towards small, low trophic level species) resulting in catches with lower market value and leading to trophic cascades and reefs dominated by macroalgae (Fisheries, Brief 1 p.78).
- Threats to biodiversity resulting in loss of coral reef resilience
- Degradation of physical habitat structure and loss of associated ecosystem services.

The reasons for declines in reef fishery species may be complex but it is clear that an ongoing



Hogfish (*Lachnolaimus maximus*), listed as vulnerable by the IUCN.



A nurse shark - one of the few species of sharks still seen regularly around Caribbean reefs.

history of overexploitation and habitat loss have played major roles (Jackson et al. 2001; Mora 2008; Paddock et al. 2009). Reefs that are protected from fishing have higher mean fish size than unprotected reefs (Vallès & Oxenford 2014) and are also the last remaining areas where apex predators such as sharks, large groupers and snappers are present in significant numbers (Newman et al. 2006).

Caribbean reef fisheries include many species harvested with multiple gear types by fishers with highly variable dependence on the fishery. Understanding these complexities is important to ensuring effective management and hence the long-term sustainability of reef fisheries.



Nassau grouper (*Epinephelus striatus*).

### Spawning aggregation protection in Belize

Fish spawning aggregations are temporary, high-density groupings of single species of fish that come together at a fixed location, often converging from distant places, for the specific purpose of reproducing. Spawning aggregations are particularly vulnerable to overfishing as they occur at predictable locations and times, meaning that fishers can target the aggregations and rapidly reduce the population size of a species normally distributed across a wide area. Throughout the Caribbean, Nassau grouper (*Epinephelus striatus*) spawning aggregations have been decimated by fishing and the species is now listed as endangered by the IUCN (Sadovy De Mitcheson et al. 2008). In Belize, about one-third of grouper spawning aggregations had disappeared by early 2000 (Sala et al. 2001). In response to this a National Spawning Aggregations Working Group was formed to monitor and validate the status of spawning aggregations. Support for protection of aggregation sites was gained by involving a wide range of stakeholders in the work, including local fishers, NGOs and government departments. Fishers were involved in research activities, being paid for their work, and training in alternative livelihoods such as SCUBA dive guiding, kayaking and fly fishing was provided. Following confirmation of broad support from fishers, the Minister of Fisheries signed legislation in November 2002 that created a closed season for Nassau grouper from December to March, and fully protected 11 spawning aggregation sites in new marine reserves. Belize now has four of the last few known Nassau grouper spawning aggregations of over 100 individuals (Sadovy De Mitcheson et al. 2008) and their successful protection should help ensure their long-term persistence.

For more information on Belize spawning aggregation protection: <http://www.reefresilience.org/case-studies/belize-mpa-design/>







## REEF FISHERY SPECIES

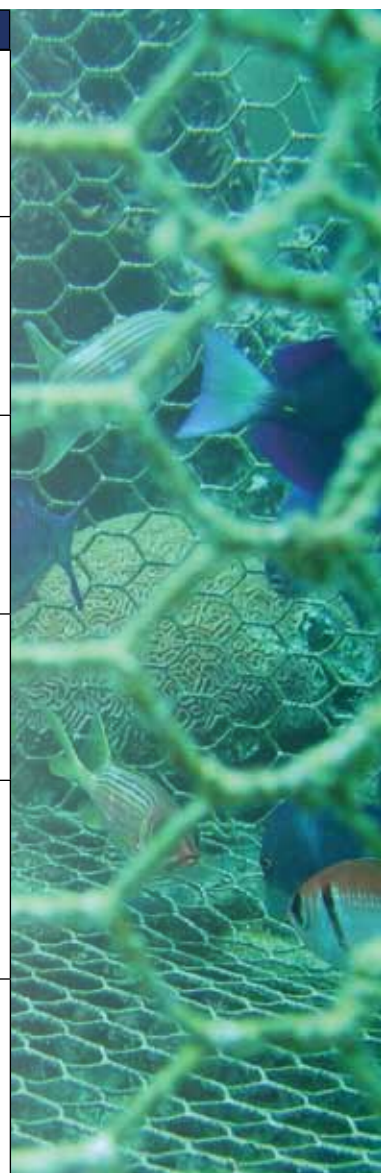
The main commercial, reef-associated fishery species in the Caribbean are conch (*Strombus gigas*), Caribbean spiny lobster (*Panulirus argus*), groupers (Serranidae), snappers (Lutjanidae) and grunts (Haemulidae). Some reef-associated pelagic species may also be considered as part of the reef fishery grouping, such as barracuda (Sphyraenidae), various jacks (Carangidae) and small tunas and mackerels (Scombridae). In areas where these species have been overfished and/or cultural preferences create demand, a variety of other reef species may also be targeted, such as parrotfishes (Scaridae), surgeonfishes (Acanthuridae), squirrelfishes (Holocentridae), octopus (Octopodidae) and sea urchins (Toxopneustidae). However, many reef fishing gears are non-selective and reef fish harvest is generally multispecies, with almost all species caught having some commercial value in local markets.



Reef fisher emptying his multispecies catch from a fish trap.

*Categorisation of Caribbean reef fisheries and description of main target species and gear*

Category	Qualifications
<b>Reef (shallow-shelf) demersal</b> 	Benthic reef fish species in <50 m, e.g. snappers (Lutjanidae), groupers (Serranidae), parrotfishes (Scaridae), yellowtail snapper ( <i>Ocyurus chrysurus</i> ), grunts (Haemulidae). Vulnerable to multiple gear types including lines, spears, nets and traps.
<b>Deep-slope demersal</b> 	Benthic reef fish species in >50 m principally groupers (Serranidae) and snappers (Lutjanidae), e.g. northern and southern red snappers ( <i>Lutjanus campechanus</i> and <i>L. purpureus</i> respectively) silk snapper ( <i>L. vivanus</i> ), queen snapper ( <i>Etelis oculatus</i> ), vermillion snapper ( <i>Rhomboplites aurorubens</i> ). Caught on deep lines or in deep set traps.
<b>Nearshore pelagics</b> 	Nearshore and coastal pelagic species that can be found in close proximity to or on reefs during some stage of their life history, e.g. horse-eye jacks ( <i>Caranx latus</i> ), scad ( <i>Decapterus macarellus</i> ), barracuda ( <i>Sphyraena barracuda</i> ). Usually caught while trolling or with a net.
<b>Conch</b> 	Conch (usually <i>Strombus gigas</i> ) gathered from shallow reef and reef associated habitats by free-diving or SCUBA-diving.
<b>Lobster</b> 	Lobster (mainly <i>Panulirus argus</i> ) gathered from coral reefs and associated habitats by free-diving and SCUBA-diving, by hand or using snares, spears, or nets (deployed around casitas) or harvested by traps set in both shallow reef and deep slope environments.
<b>Other shellfish/ molluscs</b> 	Other species found in and around reefs or associated nearshore habitats (e.g. octopus, whelks, crabs, sea urchins). These are generally gathered by hand, often by free-diving or SCUBA-diving.



## REEF FISHING GEAR

Caribbean reef fisheries are not only characterized by the high diversity of species harvested, but also by the multiple artisanal fishing gears used. Although well suited to fishing in coral reef environments, most of the gears are non-selective which complicates the implementation of species-specific management measures. Furthermore, some gears may cause environmental damage or health issues for fishers. For example, fish traps can move in bad weather causing damage to coral heads, or may be lost, but continue to 'ghost fish' for many months. Use of compressed air for diving (SCUBA or hookah gear) by untrained divers has resulted in fishers suffering death or permanent disability from decompression sickness (the 'bends').

Since most reef areas are relatively shallow and often close to shore, fishing grounds can be accessed easily by shore fishing, swimming from shore, or by small boat. Caribbean reef fishing vessels are typically small, open boats, generally powered by outboard motors or oars, and can be easily hauled ashore by hand. As such, entry into the reef fishery requires relatively low capital investment. Furthermore, the reef fishery can operate effectively with little or no shore infrastructure meaning that reef fishers may land and sell their catches along almost any stretch of shoreline. The dispersed nature of the reef fishery and typical lack of centralized landing areas means that monitoring the fishery is very difficult and therefore costly.



*Multi-purpose inshore pirogues in Bequia, St Vincent.*



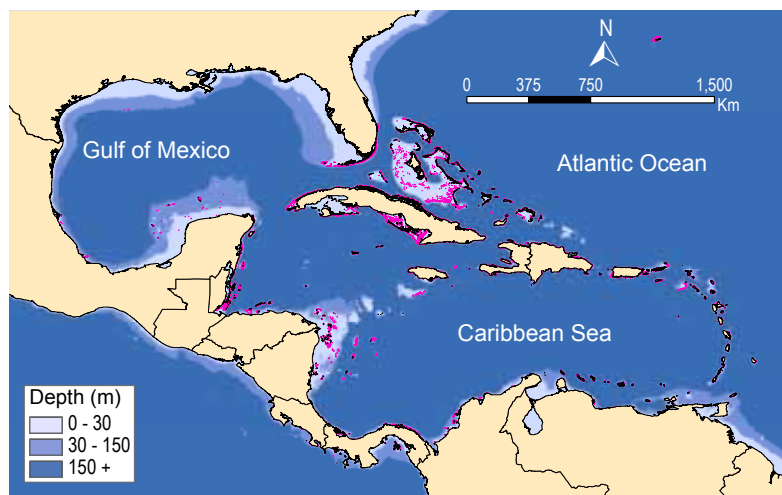
*Moses used for pot fishing in Barbados.*



*Dugouts in southern Belize.*

Fishing activity	Description of fishing activity/gear/ target species
<b>Diving (free)</b>	Free diving refers to the practise of diving without compressed air, usually with mask and fins. Harvesting may take place by hand (for species such as conch, whelks and urchins) or with the use of a handheld prying device, spear or sling, or a speargun (for species such as reef fishes, lobsters, crabs and octopus).
<b>Diving (compressed air)</b>	Compressed air diving includes SCUBA-diving with tanks as well as the use of compressed air supplied from the surface through a tube (Hookah diving). As with free diving, harvesting may take place by hand (for species such as conch, whelks and urchins) or with the use of a handheld prying device, spear or sling, or a speargun (for species such as reef fish, lobster, crabs and octopus).
<b>Line fishing</b>	Line fishing, also known as bottom-fishing, refers to fishing (usually whilst stationary) with the use of a weighted line and one or more baited hooks to target demersal reef and deep slope species near the seafloor.
<b>Trolling</b>	Trolling refers to fishing with a baited hook and line towed behind a moving boat so that the line remains close to the surface and targets epipelagic reef-associated species.
<b>Netting</b>	Netting refers to a variety of fishing activities that employ the use of a fishing net such as a hand thrown cast net or seine net that is activity fished, or a gill net or some type of tangle net that is left to fish passively. Nets may be deployed from a boat or from the shore and usually target nearshore pelagic schooling species or schooling reef fishes.
<b>Trapping</b>	Trapping refers to the method of fishing with some form of cage structure. These may be made of wire mesh (or cane) with a wooden or metal frame and a specially shaped entrance funnel, and are commonly referred to as 'fish pots'. They are used baited or unbaited to target reef fishes and lobsters. Lobster-specific traps, made of slatted wood with a specialised entrance funnel are also used, as are open, lobster-attracting artificial habitats, commonly known as casitas. These may comprise a variety of materials such as wooden pallets, a collection of short pipe lengths, shelves of galvanised sheeting, or piles of cement blocks, placed on the bottom near reef habitat to aggregate lobsters for easy harvesting by hand or net.

## DIFFERENCES AND SIMILARITIES IN CARIBBEAN REEF-FISHERIES



*Extent of Caribbean continental shelf (bathymetry breaks at 30m and 150m corresponding to end of shallow reefs and end of mesophotic reefs).*

Most coral reef fisheries in the Caribbean are based around shallow water coral reefs, i.e. those shallower than 150m. The large, shallow continental shelf areas in the northern and western Caribbean are therefore where the largest areas of coral reefs are found (Map). It is countries in these areas that are the principle exporters of two of the highest value reef-associated species, queen conch and spiny lobster. Large reef fisheries are found in the Bahamas, the Florida Keys and throughout the Mesoamerican barrier reef system (Mexico, Belize, Guatemala and Honduras). The southern and eastern Caribbean has a much smaller continental shelf area, with most coral reefs forming a narrow fringe around the islands or on offshore banks (Map). In these areas, pelagic species, such as flyingfish (principally

*Hirundichthys affinis*), dolphinfish (*Coryphaena hippurus*), tuna (including *Thunnus albacares* and *Katsuwonus pelamis*) and wahoo (*Acanthocybium solandri*) are landed in much greater quantities than reef-associated species, although reef fishing remains socially and culturally important.

### Challenges of managing reef fisheries

Several features of Caribbean reef fisheries make their management particularly challenging:

- Multispecies, multi-gear nature of the fishery
- Diversity and dynamic nature of fisher dependence on the reef fishery
- Small-scale, highly dispersed fishery with many landing sites
- Limited capacity for monitoring, assessment and enforcement (financial, social, institutional)
- Fisheries resources are frequently shared amongst multiple nations, straddling several national boundaries
- Multiple uses – reef resources have important non-extractive value for tourism (Services Brief 1 p.108).

Traditional fisheries management has focused on maintaining catch of a single species at or near a desirable reference point - the maximum sustainable yield (MSY) (Pikitch et al. 2004). Whilst there are a few examples of this single species MSY approach being used in the Caribbean, such as in the management of the industrial queen conch fishery of Pedro Bank, Jamaica (Aiken et al. 2006), producing estimates of MSY requires extensive fisheries data that are not available in most Caribbean nations. Currently all fisheries

### Reef fishers

A further challenge to managing reef fisheries in the Caribbean is the diverse nature of reef fishers themselves and their varying dependence on the reef resources for livelihood support. Reef fishers often remain unregistered and may have multiple, dynamic sources of income besides reef fishing, including income from alternative fisheries as well as from agricultural, construction or tourism sectors. Research from nine study sites in Belize, Honduras and St Kitts and Nevis found that reef fishers' dependency on income from reef fishing ranged from 31 – 69% and the number of other occupations held by the average fisher ranged from 1.5 – 2.6 occupations per fisher (Gill 2014). As such, reef fishers may be able to maximize their income and minimize livelihood risk by switching between full and part-time reef fishing, depending upon personal circumstances, changes in the seasonal availability of other fishery species, and the availability of work in other sectors.

The movement of fishers in and out of the reef fishery and seasonal changes in availability of fish can complicate any efforts to manage fisheries. An understanding of how fishing forms a part of many people's livelihoods is therefore necessary for any effective management measure (Livelihoods p.136).

*Some fishers are becoming involved in the lionfish fishery.*



stock assessments in the region, excluding U.S. territorial waters, are considered data limited (Salas et al. 2007; Michaels et al. 2013). Even in the U.S. Gulf of Mexico where there is considerable investment in fisheries management and research, only one reef fishery species, the red snapper, has a defined MSY (NMFS 2009).

Crude multi-species estimates of MSY for coral reefs are  $4 - 5 \text{ mt km}^{-2} \text{ yr}^{-1}$  (Burke & Maidens 2004; Newton et al. 2007) with MSY for Jamaican reefs estimated as  $4.1 \text{ mt km}^{-2} \text{ yr}^{-1}$  in 1983 (Munro & Thompson 1983). However, these values are based on coral reef fisheries yield data that are more than two decades old (see Dalzell 1996 for a review of principle sources) and current MSY values for the Caribbean are likely to be significantly lower due to further reef degradation and fisheries overexploitation since these estimates were made (Hughes 1994; Gardner et al. 2003).

Of particular concern is the fact that conventional single species assessment and management invariably fails to take account of the complex nature of coral reef communities. Coral reef fishery species are dependent on the reef habitat, hence changes in that habitat will affect the species, e.g. as reefs lose their 3-D structural complexity, the abundance and biomass of fish decreases (Resilience Brief 5 p.42). Fishing can also have unpredictable effects on the biomass of species on reefs as the balance between predators and prey is changed (Fisheries Brief 1 p.78). Consideration of the entire ecosystem is therefore required for effective management of coral reef fisheries.

To integrate consideration of the ecosystem into fisheries management a new approach is needed, namely ecosystem-based fisheries management (EBFM). This approach is being widely adopted by fishing authorities and managers worldwide and is being strongly encouraged in the region, being particularly well suited to management of complex fisheries systems like those of coral reefs.

Conventional fisheries management has been 'top-down', principally led by governments. This approach is widely accepted to have been unsuccessful at ensuring sustainability of small-scale fisheries resources (Mahon et al. 2011). Although a considerable number of regional fishing bodies exist (Chakalall et al. 2007), the regulations that they have produced have been poorly enforced in most places due to lack of capacity, funding and willingness amongst local governments. The EBFM approach incorporates the Food and Agricultural Organisation (FAO)

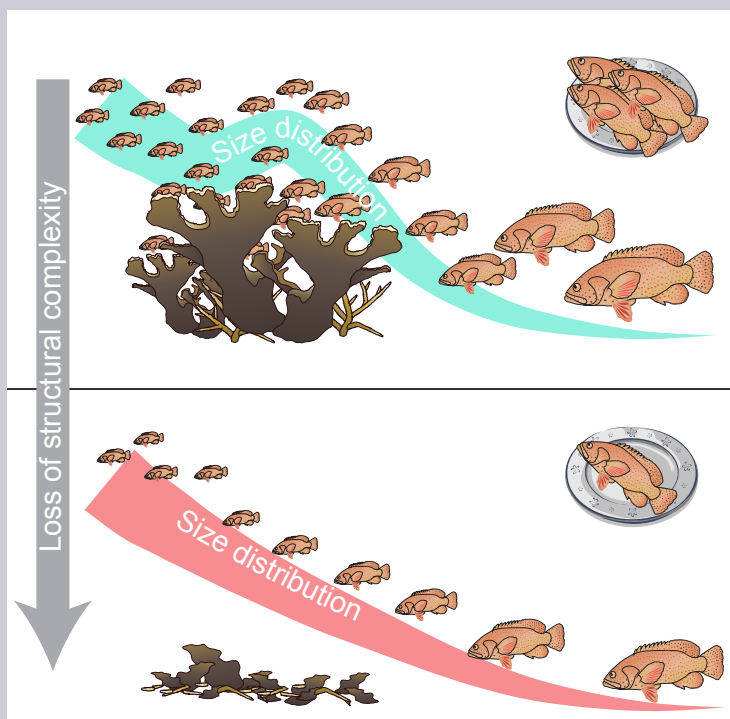
Code of Conduct, which stresses the need for improved governance to ensure the success of any management measures. This includes transparency, stakeholder involvement and cooperation of all states involved in harvesting fish stocks.

### Linking coral reef complexity and fisheries productivity

*Corals create an amazingly complex habitat made up of lots of holes, cracks and crevices that serve as hiding places and homes for a huge abundance and diversity of organisms. This structural complexity is vital for the productivity of reef fisheries. Using data from coral reefs in the Exuma Cays Land and Sea park in the Bahamas, researchers created a food web model to understand the effects of reduced structural complexity on fisheries productivity. Initial results from the model suggest that a complete loss of structural complexity may reduce fisheries productivity 3-fold, i.e. three-times less potential catch.*

*Reefs with high structural complexity provide lots of predation refugia for vulnerable organisms, including juvenile and small-bodied fish. When this complexity is lost however, the dynamics of the reef community change. Increased mortality results in fewer small and medium-bodied fish, and in turn results in fewer fish overall. There is an associated decline in the rate that energy is transferred up the food web meaning less food is available for large-bodied fish that are valuable to reef fisheries.*

*Maintaining a structurally complex reef is therefore important for the thousands of people who rely on reef fisheries for food and livelihoods.*



*Structurally complex reefs have more fish and higher fishery productivity than low complexity reefs.*

### FURTHER INFORMATION

Rogers A, Blanchard JL, Mumby PJ. 2014. Vulnerability of coral reef fisheries to a loss of structural complexity. *Current Biology* 24 (9) pp. 1000 - 1005

# ECOSYSTEM-BASED MANAGEMENT OF CORAL REEF FISHERIES

A switch to ecosystem based fisheries management (EBFM) is being promoted by a number of organizations including the FAO, International Union for Conservation of Nature (IUCN) and UN Environmental Programme (UNEP). Within the Caribbean the uptake of EBFM will be accelerated by the Caribbean Large Marine Ecosystem (CLME) project, which is assisting participating countries improve marine resource management, principally through an ecosystem-based management approach (see [Governance Introduction for more on CLME](#)).

Many definitions of EBFM exist, but the following provides a short and simple summary:

***"The key management goal is not to maximize fisheries catch, but to maintain the ecosystem in a state that will lead to sustained production."*** (Appeldoorn 2008)

Compared to traditional fisheries management that was focused on maximizing fisheries yields (MSY), EBFM focuses on maintaining a healthy ecosystem to ensure long term productivity of the fisheries which are themselves an integral part of the ecosystem. A further contrast is the focus on stakeholder responsibility in EBFM, rather than conventional management's top-down control.

EBFM is not characterized by a single indicator or management principle but rather is based on first principles that can be used to develop a management strategy. The principles for EBFM of coral reef fisheries (modified from Appeldoorn 2008) are listed below.

## **Rigorously protect structural habitat**

Not only reefs, but adjacent habitats such as mangroves and seagrass beds, provide essential habitat to reef fishes at different stages of their life cycle, e.g. the largest herbivore in



Coastal land clearing.

the Caribbean, the rainbow parrotfish, *Scarus guacamaia*, requires mangroves as a juvenile habitat and removal of mangroves has resulted in local extinctions of this species (Mumby et al. 2004; Dorenbosch et al. 2006). Management that focuses not only on protecting the extent of the habitat, but also on ensuring that the habitat quality is maintained is key, because structurally complex reefs have much higher fish productivity than flattened reefs ([Linking coral reef complexity p.71](#)).

## **Protect water quality**

Sediment, excess nutrients and other pollutants in the water can all damage the natural functioning of coral reefs. Maintenance of water quality requires management of the entire watershed, highlighting the importance of an integrated coastal zone management approach. ([Resilience Brief 1 p.34](#) and [Brief 2 p.38](#))

## **Maintain ecosystem integrity and function**

There are numerous complex interactions among the habitats and species that together form an ecosystem. Fortunately it is not necessary to understand all of these ecosystem interactions. Instead the management focus should be on maintaining ecosystem integrity and function. This includes maintaining

(left) Mangroves are important nursery areas for some reef species.

(right) Juvenile conch in seagrass, Bahamas.





*Acropora sheltering reef fishes. Structurally complex reefs have much higher fishery productivity than low complexity reefs.*



*Weighing a mixed reef fish catch. Monitoring of reef fisheries provides important data to help reef managers.*

biodiversity (to improve reef resilience) as well as ensuring that key functional components remain intact such as herbivory, predation, nurseries, migration, shelter and reproduction. In practice this can translate into a wide range of management actions including: protection of key herbivore populations (Resilience Brief 6 p.45); protection or rehabilitation of nursery habitats (e.g. mangroves, seagrass beds); protection of spawning aggregation sites and population sources of both corals and fishes (Mumby et al. 2004; Sadovy & Domeier 2005; Jones et al. 2007). To help managers understand connectivity of fish stocks and coral populations, new tools are being developed (Fisheries Brief 8 p.92). In certain circumstances reef rehabilitation may be a useful measure to help restore lost ecosystem function (Resilience Brief 8 p.48).

### Select reference points and indicators for monitoring

While EBFM does not depend on high resolution fisheries data, monitoring is required to provide feedback for managers on whether the fishery is meeting its objectives and whether the ecosystem is changing. This is essential for assessing the impact of fisheries and effectiveness of management measures. The indicators to be monitored will depend on the goals and objectives set for the fishery, but are likely to include fishery specific indicators (e.g. landings, prices, number of fishers employed, etc) and ecological indicators tracking ecosystem health (e.g. hard coral cover, dominance and canopy height of macroalgae, mean fish size, etc.). In Caribbean coral reef fisheries there is an urgent need to develop fishery and ecological indicators that are informative but easy to monitor. One such example is the use of simple indicators based only on length-frequency data which have been applied in the case of the speargun fishery in Belize to determine the status of reef fishery species such as groupers, snappers and parrotfishes (Babcock et al. 2013). The three indicators used and their rationale are as follows (from Froese 2004):

- Percentage of mature fish in catch, with 100% as target – so that each fish has a chance to spawn at least once before harvest.
- Percentage of individuals with optimum length in catch, with 100% as target – targeting these individuals avoids removing smaller fish which are best left to grow to maximize the fishery yield.
- Percentage of 'mega-spawners' in catch, with 0% as target and 30 – 40% if no upper size limit exists – avoid removing the most fecund individuals (those which produce disproportionately more eggs).

Further development of simple size-based metrics to indicate fishing status and grazing function on Caribbean reefs has revealed the value of using individual fish mean size for the parrotfish assemblage (Fisheries Brief 4 p.84).

Comparisons between fished and unfished areas are important to understanding the effects of fishing relative to other natural and anthropogenic impacts. Unfished marine reserves are frequently used for this purpose. When making such comparisons, however it is important to take into account habitat differences between different areas of reef, e.g. reefs dominated principally by boulder star coral species (*Orbicella* previously *Montastraea*) will have different fish assemblages compared to reefs dominated by gorgonian sea fans (Harborne et al. 2008).

### Employ a precautionary approach at all times

The precautionary approach to fisheries as developed in the FAO Code of Conduct recognizes the natural uncertainty and risk in attempting to manage fisheries. Management measures taken in light of the precautionary approach should be based on the best scientific advice available, taking into account the uncertainty in the advice and the risk that the fishing activity poses to the functioning of the ecosystem.

Parrotfish with cocoon at night time.



An example of management according to the precautionary approach is the ban on parrotfish harvesting that has been implemented in Bonaire and Belize. Parrotfish are vital to the health of Caribbean reefs due to their role as grazers. The maximum sustainable yield for parrotfish is currently unknown and any attempt to set a limit on harvesting will have to take into account their important role in the ecosystem, hence banning harvesting is a good precautionary approach until improved scientific advice is available (Resilience Brief 6 p.44). However, the zoning of vital habitats where parrotfish harvesting is prohibited is an alternative, though less conservative solution (Fisheries Brief 6 p.88).

## Recognize limits to production and control rates of extraction

The natural rate of production (growth and reproduction) of a fish population ultimately controls the rate of sustainable harvest that is possible. Fishing can affect production rates by changing the population biomass, as can other environmental variables such as habitat availability and water quality. If the rate of fishing continuously exceeds the rate of production, fish stocks will be depleted, with negative consequences on the whole ecosystem. A basic principle is to control fishing practices that reduce production. This involves taking into account the life history of fishery species, e.g. large, long lived species tend to have much lower production rates compared to smaller, short lived ones. Groupers and large snappers have been overfished in many areas of the Caribbean in part due to their slow population growth rates, late maturity and tendency to form spawning aggregations which can be easily targeted by fishers (Protection of spawning aggregations in Belize p.67). To reduce fishing pressure on these species with vulnerable life-histories, more resilient fishery species, such as yellowtail snapper have the potential to support sustainable fisheries (Fisheries Brief 2 p.80).

Careful fisheries management can ensure the health of the ecosystem and sustainable fish stocks.



Fundamentally, food webs (trophic balance) should be maintained (e.g. stocks of prey fish are needed to provide food for larger, preferred fishery species) and juveniles must be allowed to reach sexual maturity and spawn. Furthermore, since fishery species typically become exponentially more fecund with increasing body size, there is merit in considering implementation of a maximum legal size limit to protect the individuals with the greatest reproductive capacity. This is especially important for those long-lived species with slow individual growth rates but large maximum sizes (e.g. large snappers and groupers). These measures, combined with marine reserves, which would allow individuals to reach their maximum size, could help increase populations of important fishery species (see Select reference points and indicators for monitoring p.73).

## ECOSYSTEM-BASED MANAGEMENT ACTIONS

Management action	Purpose
Marine reserve networks	Provide control areas for comparison with unprotected areas Protect spawning stocks, trophic structures, essential fish habitat Control fishing effort Protect biodiversity
Close spawning aggregations	Protect highly vulnerable spawners
<b>Gear restrictions</b> <ul style="list-style-type: none"> <li>• No entangling nets</li> <li>• No spear guns</li> <li>• Use large mesh</li> <li>• No fish traps</li> </ul>	<ul style="list-style-type: none"> <li>• Protect herbivores and small reef species</li> <li>• Protect sharks and turtles</li> <li>• Protect predators and slow moving species</li> <li>• Protect spawners, reduce by-catch, fishing mortality and growth overfishing</li> <li>• Reduce ghost fishing and physical damage to reef</li> <li>• Reduce growth overfishing and protect juveniles and non-target species</li> </ul>
Monitor catch and status of only a select and representative number of species that are important ecologically or economically (e.g. lobster, conch, red hind, red snapper, yellowtail snapper)	Focus limited resources on obtaining the level of data required for assessment of reef health Track management effectiveness
Transboundary management of species using new tools for measuring connectivity of reef species (Fisheries Brief 8 p.92)	Ensure persistence of major sources of larvae Maintain connectivity of larval populations throughout the region
Manage watershed – reduce sediment and nutrient run-off from land	Protect water quality and habitat
Minimize impacts of coastal development, with an emphasis on improving the quality of environmental impact assessments	Protect water quality and habitat
Reduce or stop output of sewage and untreated waste water into coastal environment	Protect water quality
Incorporate monitoring of reef ecosystem health (e.g. from coastal zone management programmes)	Track efforts to protect ecosystem health, e.g. water quality and habitat
Adopt co-management practices wherever possible	Incorporate stakeholders as part of the decision making process Increase sense of ownership and management responsibility
<b>Assessments</b> <ul style="list-style-type: none"> <li>• Ecosystem or community based metrics</li> <li>• Selected species assessments</li> <li>• Simple multispecies approaches</li> </ul>	<ul style="list-style-type: none"> <li>• Monitoring of community catch composition, size structure, trophic structure, etc.</li> <li>• Protect key species</li> <li>• Groundtruth system</li> </ul>

## REAL MEN

use their hands



Bans on spearfishing are common in marine reserves.



Monitoring catch in Honduras.



Watershed management in Newtown, St Kitts and Nevis.

### FURTHER INFORMATION

The Food and Agricultural Organization of the United Nations (FAO) has developed an online toolbox to guide users through the process of management planning and selecting appropriate tools for EBFM: <http://www.fao.org/fishery/eaf-net/en>  
The website is recommended for managers wishing to gain a fuller insight into the implementation of EBFM.



## Henri Vallès

CERMES, University of the West Indies

### MY RESEARCH

I am working on trying to identify indicators that can be used to assess the health of reef fish populations, those populations that are actually fished, and finding ways that the information can be transferred and disseminated to different interest groups like fishers, policy makers and managers so that they can improve decision-making and make more informed decisions.



*I am half Haitian and I lived in Haiti for many years. As you know, Haiti is a very poor country so many people rely heavily on what can be extracted from the sea. Just living there is an eye opener about how important the sea is to the Caribbean communities.*

*Regarding changes to coral reefs I'm not that old but if you go to some parts of Haiti, in the south part of Haiti where I worked for some time and look at the kind of tools that they use to capture fish it is not rare to run into fish pots or fish traps that have a mesh size that you can barely put your finger through. That generally is a strong indicator that the system is very, very heavily fished and that people are trying to extract as much as they can just to make ends meet. So there is clear evidence that something needs to be done and that things are not going the way they should. Yes, I think things have changed.*

**The system is very, very heavily fished and people are trying to extract as much as they can just to make ends meet.**

1

Fishing down the food  
web: ecosystem effects  
of fishing



2

Building a sustainable  
yellowtail snapper fishery  
on Caribbean coral reefs



3

Identifying fishing grounds  
across small spatial  
scales: a low-cost fisheries  
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4

Parrotfish weight as an  
indicator of fishing  
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5

Understanding and  
managing  
invasive lionfish



6

Managing parrotfish  
harvesting with habitat  
protection zones



7

Using vessel monitoring  
system data for sustainable  
management of reef  
resources



8

Using connectivity  
for the transboundary  
management of reef  
species



# Fishing down the food web: ecosystem effects of fishing

*Fish caught in net.*

## THE EVIDENCE

Many reefs throughout the Caribbean have been overfished for decades, however Belize has a relatively low human population density and a large barrier reef, so fishing pressure on the reef had been relatively low until recently. Grouper and snapper were the main fin fishery species in 2002 but over a 7 year period, these fishes were reduced in abundance. The numbers of grouper declined dramatically, with the chance of seeing a large grouper on a survey transect dropping 10-fold from 21% in 2002 to 2% in 2008/2009. The abundance of large snappers also underwent similarly large decreases. Parrotfish were not previously targeted by fishermen, but from 2004 to 2008, they went from being found in just 6% of fishermen's catches to approximately 20%. This change was principally due to the difficulty in catching preferred groupers and snappers.

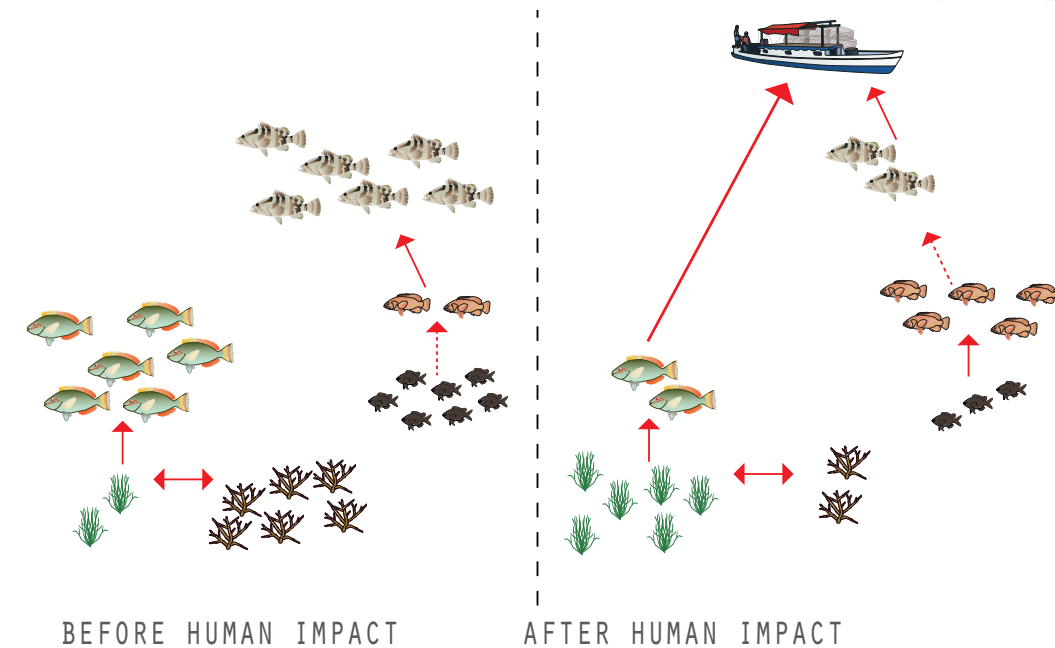
*Smaller reef fishes are susceptible to trap/pot fishing.*

## THE ISSUE



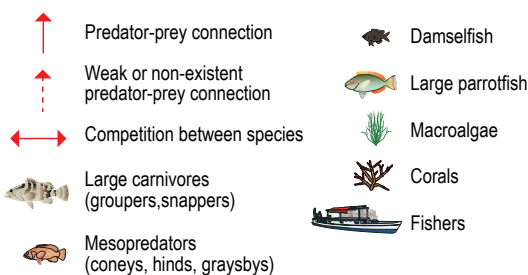
*Fishing is an important source of employment, food and income for many people within the Caribbean, including some of the poorest. The health of reef fish stocks is important not just for the fishers but also the tourism industry, as divers and snorkelers like to see large and diverse fish populations on reefs. Furthermore, reef fish are a vital part of the ecosystem, with herbivores, such as parrotfish, grazing on algae and thus allowing new corals to settle and grow on the reef.*

*In many of the world's fisheries, humans have gone through a process of 'fishing down the food web'; depleting first the large carnivorous fish then progressively smaller and generally less desirable species. On coral reefs this has meant sharks, groupers and large snappers have been fished to very low levels in many places, so fishers have started to target smaller and less desirable fishes such as parrotfish. This can have negative effects on the coral reef ecosystem as a whole not just the reef fish populations.*



### FOOD WEB

Simplified food web shows the effect of fishing reducing the numbers of large carnivores and parrotfish, which allows their food sources to increase in abundance. Note how the cascading effects of decreased abundance of parrotfish ultimately results in decreased coral cover.



This 'fishing down the food web' has cascading effects through the food chain. When the numbers of groupers and large snappers are reduced, their prey, mesopredators (middle level predators) such as hinds, coneys and graysbys, increase in numbers and size because they have fewer predators. These effects continue down through the food chain in what is referred to as a trophic cascade. A cascade can lead to unexpected effects on the coral reef ecosystem. For example, the increase in numbers of mesopredators will result in a reduction in the numbers of their prey, which include small-bodied reef fish such as damselfishes and juveniles of many species.

Fishing of parrotfishes is of particular concern as they are the principal grazer of algae on most Caribbean reefs today. If numbers of parrotfish are reduced too far, the cover of macroalgae on the reef will increase. This in turn can reduce the amount of coral cover as macroalgae has a range of effects including reducing rates of coral larvae settling on the reef, and competes with corals for space.

### FURTHER INFORMATION

Mumby PJ, Steneck RS, Edwards AJ, Ferrari R, Coleman R, Harborne AR, Gibson JP. 2012. Fishing down a Caribbean food web relaxes trophic cascades. *Marine Ecology Progress Series* 445: 13–24. Available at: <http://dx.doi.org/10.3354/meps09450>

## MANAGEMENT IMPLICATIONS

### Monitoring of reef fishery

This provides information on changes in the composition and abundance of fish caught and can help identify signs of fishing down the food web, such as increasing catches of parrotfish. Where regular monitoring is not feasible due to lack of resources, qualitative information on fish catches can be obtained by talking to fishers and regularly visiting fish markets.

### Ban on parrotfish fishing

Belize and Bonaire have both implemented bans on fishing for parrotfish. Given the ecological importance of parrotfish for corals (as a grazer of algae), it is worth considering a ban. Alternatively management could aim to reduce fishing pressure on the large-bodied parrotfish, e.g. stoplight parrotfish, *Sparisoma viride*, and redband parrotfish, *Sparisoma aurofrenatum*, which are the most important grazers of algae.

### Indicators of overfishing

Increases in abundances of mesopredators is an indicator of overfishing of larger predators (large groupers and snappers) which normally prey on these species. However it is important to note that fishers might shift to target mesopredators as the process of fishing down the food web continues, hence this effect might not be noticed in a heavily exploited fishery.



## Building a sustainable yellowtail snapper fishery on Caribbean coral reefs

*Yellowtail snapper (Ocyurus chrysurus).*

Identifying suitable fish species for exploitation and developing effective management are critical goals for coral reef managers. Here we provide evidence that the yellowtail snapper (*Ocyurus chrysurus*) is a good candidate for a species specific management policy to underpin the development of sustainable fisheries, particularly in the Western Caribbean.

### THE EVIDENCE

Yellowtail snapper has life history traits advantageous to being more resilient to fishing pressure than several other snapper and grouper. These traits include a relatively fast growth rate, sexual maturity at around two years or 25cm, year-round reproduction and an omnivorous diet that includes plankton

Found across the wider Caribbean, yellowtail snapper are one of the most important components of local fisheries both by weight and value in the Western and Southwestern Caribbean. As adults, yellowtail form loose shoals in surface waters near the drop off on coral reefs and are easy to catch using hook and lines which is a highly selective method with little bycatch. In the Western Caribbean, genetic studies suggest that yellowtail snapper form a meta-population with large levels of mixing, but local recruitment is also relatively high. At smaller scales, juveniles from seagrass beds are connected to adult grounds including offshore reefs, across tens of km, meaning local coastal protection is important for local fisheries.

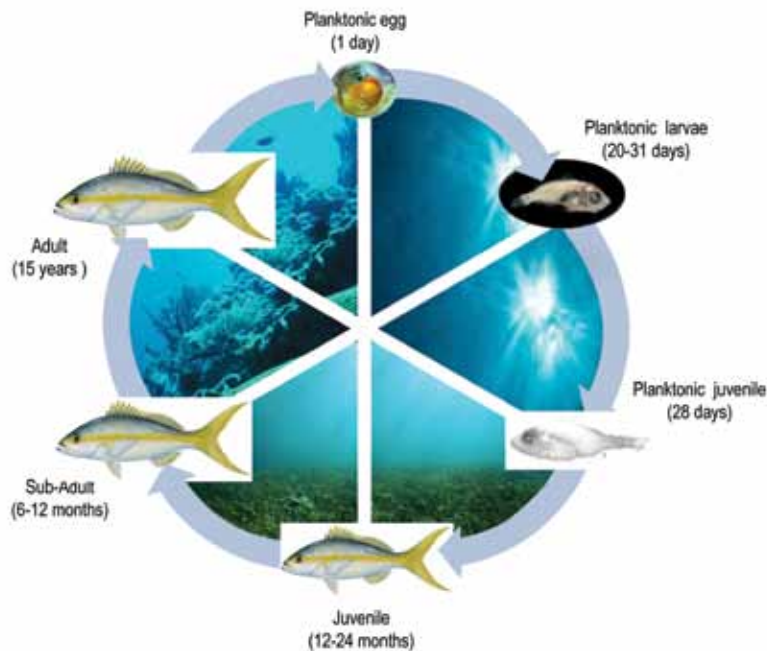


*Unloading reef fish catch in the Bay Islands, Honduras.*



*Grouper and snapper are top predators that are important components of Caribbean fisheries and part of the culinary heritage of the region. Unfortunately, the majority of snapper and grouper species are highly vulnerable to overfishing, due to slow growth rates and late maturity, in addition to forming predictable spawning aggregations to reproduce. Targeting these spawning sites has reduced their reproductive capacity and been a principal cause for the collapse of populations of Caribbean species such as the Nassau grouper (*Epinephelus striatus*) and the Cubera snapper (*Lutjanus cyanopterus*) throughout the region. As traditional grouper and snapper fisheries decline, fishers increasingly switch to target alternative reef species, often deploying unselective fishing methods such as nets and traps to increase catch volume as a trade-off against lower catch quality and poorer market value.*

*Shifting to mixed species fisheries on coral reefs presents complex challenges as each species may respond differently to management interventions. In addition many smaller coral reef species such as parrotfish play essential ecological functions as parrotfish are essential grazers of algae, preventing reefs being overgrown by algae.*



## MARKET VALUE

Yellowtail snapper with its white flesh and subtle flavour is a valuable fish species, comparable to other larger snapper or grouper. A staple of local western Caribbean cuisine it also has a strong market price in the United States where there is a price increase for larger individuals. This means there is an economic incentive for fishers to target larger individuals and leave smaller fish to grow.

*The yellowtail snapper's life cycle and shifts in habitat use with growth and size.*

## FREQUENTLY ASKED QUESTIONS

***We have limited resources for fisheries management why should we prioritize the management of yellowtail?***

Ensuring a sustainable yellowtail snapper fishery could avert coral reef fisheries decline and fishers shifting to target other reef fish which are essential for ecosystem function. Stopping this slide in fisheries productivity can prevent more drastic fisheries restrictions in the future such as complete closures. A sustainable yellowtail fishery is a valuable renewable resource for coastal communities. Enabling fishers to target yellowtail snappers sustainably can provide employment whilst allowing the protection of critically endangered species such as the Goliath and Nassau groupers.

***There is limited budget for data collection what type of fisheries data should be collected?***

Developing a specific management plan for yellowtail snapper can be a sequential process, but it is important to establish regular monitoring of catch and effort levels. This can be best achieved by working with the fishers so they become part of the data collection process. Yellowtail fishers could be registered under a specific license to facilitate this process.

## MANAGEMENT IMPLICATIONS

Where management has been implemented, yellowtail snapper populations have responded well. For example no-take zones in the Florida Keys found an increase in population biomass of 15% after only 3 years whilst a minimum size and total allowable catch has ensured the fishery has consistently remained sustainable since reviews began in 2000.



***Are there tools available that can help collect and analyse fishing data?***

Free tools such as [www.ourfish.org](http://www.ourfish.org) are available to assist fisheries managers and local fishermen develop a fisher register, compile catch statistics and monitor fisheries infractions.

***What research would help develop a sustainable fishery?***

Monitoring how many fish are being taken out of a given area is fundamental to fisheries management. Collecting systematic data on fishing effort, location and catch composition is therefore essential to underpin good decision-making in fisheries and should be a priority for any research program. Specifically for the yellowtail snapper, since this fish utilizes different habitats throughout their life cycle, from planktonic larvae through seagrass and mangroves as juveniles and on to coral reefs as adults, their populations may be connected across large distances. Defining these connections and identifying areas of critical habitat can inform managers of the suitable spatial scale at which the fishery could be managed and also help local fishers identify exclusive or shared fish stocks across their fishing grounds.

Policy Options	Conservative		
	Most	Less	Least
Set minimum size for yellowtail snapper at 25 cm (12"), ¾ lb (350g)	•	•	•
Replace J hooks with circle hooks to reduce hooking mortality in juveniles	•	•	•
Collect yellowtail snapper as a discrete category in fisheries statistics	•	•	•
Prohibit unselective gears like traps and gill nets from coral reef fisheries	•	•	
Closed season during peak reproductive months	•		
Protect identified nursery areas in seagrass	•		

## Identifying fishing grounds across small spatial scales: a low-cost fisheries management tool

*Yellowtail snapper (Ocyurus chrysurus).*

### THE EVIDENCE

Twenty-one body measurements of approximately 100 adult yellowtail snapper from five fishing grounds across the Honduran north shore were taken. Using statistical analysis researchers identified five distinct body forms. These body forms were found to predict the fishing grounds from which the fish were taken with a high level of accuracy (min.90%; max. 100%). Distances between fishing grounds varied from a minimum of 5 kilometers up to 70 kilometers, highlighting that this technique works well over distances relevant to small-scale fisheries management.

### HOW IS IT DONE?

To determine the body form for a specific fishing ground, a total of 30-50 fish are recommended to provide a suitable sample size. It is important that the exact locations of the fish being sampled are recorded using GPS coordinates. Fish can either be caught by fisheries personnel or measured at the landing site, as long as the fisher provides the exact location where the fish were caught. Sampling can be conducted year round, however it is better to use samples from the same seasons, such as wet or dry.

*Hand line fishing.*

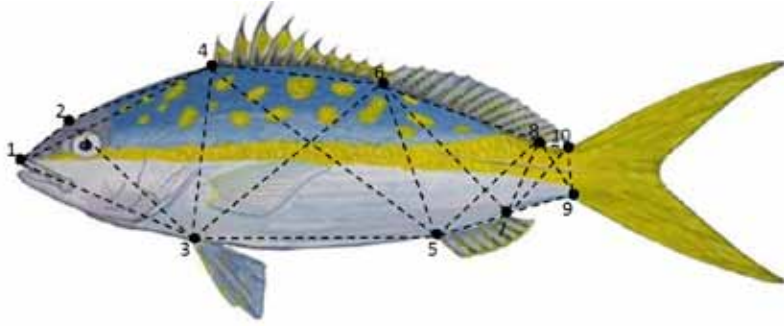
*Fisheries managers frequently have to manage dispersed fishing communities exploiting different fishing grounds spread over extensive geographical ranges. For effective management of fisheries, managers need data on how fishing pressure is distributed. A simple tool to match individual fish to fishing grounds can provide vital data for fisheries management and monitoring.*

*Several techniques have been developed to differentiate fishing grounds, but many require considerable financial and technical resources, which are often not available in developing countries or small islands. Morphometrics (quantitative measurements of body shape) offers a low-cost, relatively simple tool for fisheries managers. In the Western Caribbean the yellowtail snapper is an important species in both the small-scale and industrial fisheries. For example, in Honduras yellowtail snapper comprise up to 30% of total reef fish landings.*

*Yellowtail snapper fishing grounds within a small-scale fishery were successfully differentiated using morphometric measurements demonstrating that body measurements can be used by managers to identify the origin of landed catches.*



## FREQUENTLY ASKED QUESTIONS

**Morphometric truss network measurements**

1-2	1-3	1-4	2-3	2-4	3-4	3-5
3-6	4-5	4-6	5-6	5-7	5-8	6-7
6-8	7-8	7-9	7-10	8-9	8-10	9-10

Diagram of the ten truss points and measurement network used in the morphometric analysis, the table highlights the specific measurements and their order (from left to right) in which the measurements should be recorded.

Each fish needs to be given an identification code, which identifies the fishing ground where it was caught as well as distinguishes the individual fish. The measurements taken for each fish include the total length and fork length which should be measured to the nearest millimeter using a fish board. Ten pins are then inserted into the flesh of the fish at specific truss points. A series of 21 measurements are then recorded according to the truss network. These measurements are recorded to 0.1mm precision using calipers and together make up the 'body form' of the individual fish. The time required per fish is approximately 10-20 minutes and decreases with experience. This tool is best suited for trained fisheries officers to conduct in the field or in the laboratory and ideally should be conducted by the same person (or team) to ensure consistency in measurements.

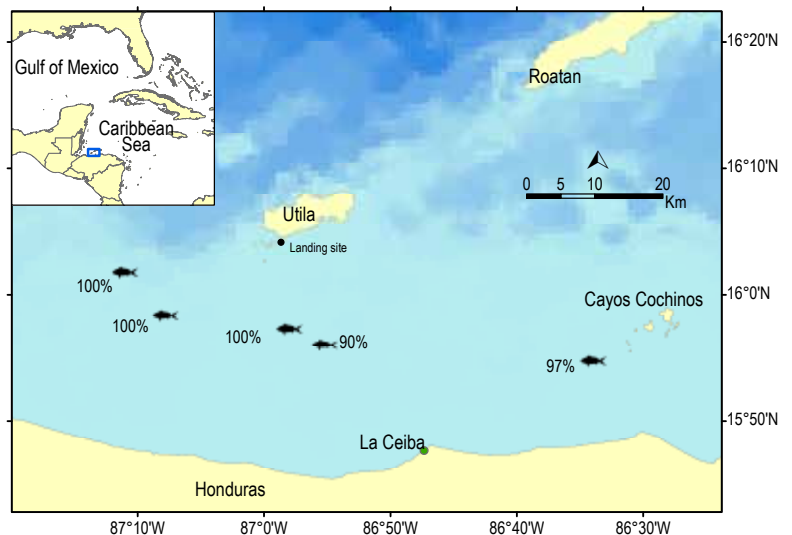
Each of the truss measurements is scaled by dividing them by the total length of the fish. A discriminate analysis is then conducted which will assign individual fish to specific fishing grounds based upon the individuals truss network measurements. The discriminate analysis produces a table highlighting the number of individuals successfully assigned to their sampling site, and where mismatched individuals were assigned. If there is confusion between closely situated fishing grounds, these grounds can be pooled, then the discriminate analysis can be re-run. Once a fishing ground has a body form defined for it using this method, it is possible to randomly sample fish at the landing site and identify the fishing ground where the fish were caught using the truss measurements.

**Is this technique applicable to juveniles?**

In the same study we were able to assign juveniles to nine different nursery grounds with a mean assignment accuracy of 89%. Due to variations in growth rates of different anatomical features of juveniles in comparison to adults, morphometric data cannot be used to compare adults and juveniles to determine connectivity within a population.

**What other techniques are available?**

Genetic analyses, using microsatellites and mitochondrial DNA, have been successfully used to trace individual fish to specific fishing grounds. These techniques require greater financial investment and technical resources which are not available to all fisheries managers and in addition there is often a long delay between sampling and receiving outputs.



Map of the five fishing grounds off the coast of Honduras identified using morphometric measurements. Accuracy of assignment of fish to fishing grounds shown as percentages.

**MANAGEMENT IMPLICATIONS**

This simple tool allows for relatively quick and easy assignment of landed catch to fishing grounds which can be useful in spatial management of fisheries, such as:

- Setting quotas for specific fishing grounds
- Implementing managed access across fishing grounds
- Enforcing no-take zones
- Establishing seasonal closures of fishing grounds.



## Average parrotfish weight as a simple but useful indicator of fishing pressure

*Juvenile and adult striped parrotfish (Scarus iseri).*

### THE EVIDENCE

Analysis of Atlantic Gulf Rapid Reef Assessment (AGRRA) survey data for the Caribbean region revealed that average fish weight of the parrotfish assemblage (for parrotfish > 5cm in total length) can be used as a simple indicator of fishing pressure in the Caribbean.

As fishing pressure increases: (1) the average body size of each parrotfish species decreases; and (2) small and large bodied parrotfish species become more and less abundant respectively. One way to measure these size-dependent changes in the parrotfish communities is by simply calculating the average fish weight of the entire parrotfish community. For example, average parrotfish weight in areas that have some protection against fishing is larger than in unprotected areas, and average parrotfish weight decreases as proxies of fishing pressure (such as human population size) increase across the Caribbean region.

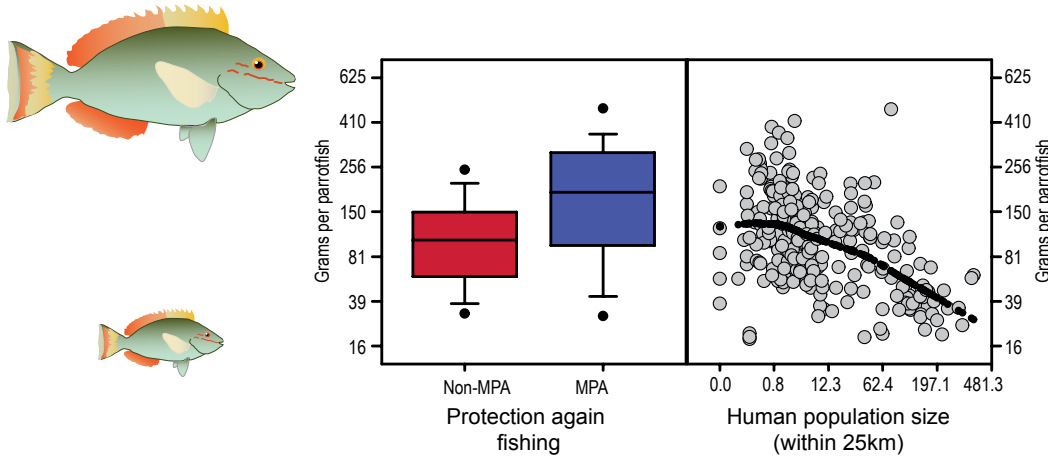
*The midnight parrotfish (Scarus coelestinus) is the second largest parrotfish in the Caribbean.*



*Coral reefs of the Caribbean are being seriously threatened by a combination of local (e.g. land-based run-off; overfishing; storm and hurricane damage) and global stressors (e.g. climate change). Evidence is mounting that the capacity of coral reefs to withstand and recover from global stressors hinges upon minimizing the negative effect of local stress.*

*Overfishing is widely recognized as one of the most important local stressors affecting reefs across the Caribbean region. One step towards managing fishing is the identification of indicators of fishing pressure that respond quickly, strongly and predictably to fishing. These indicators need to be easily measurable, simple and intuitive, so that they can be readily implemented and communicated across different stakeholder groups involved in decision making.*





*Changes in average fish weight of the entire parrotfish community (fish > 5cm TL) as a function of protection against fishing (left-hand graph) and human population size (a well established proxy of fishing pressure; right-hand graph) across the Caribbean region. The two fishing pressure indices operate at different spatial scales yet they both exert a significant ( $p < 0.05$ ) and predictable effect on average parrotfish weight.*

Links with fishing pressure were stronger for average parrotfish weight than for traditional indicators based on the average fish weight, abundance or biomass of snappers and groupers, because these highly-valued commercial fish groups are now in very low abundance on most Caribbean reefs. Average parrotfish weight is also a better indicator of fishing pressure differences among reefs than total parrotfish biomass or density.

## MANAGEMENT IMPLICATIONS

Average weight of the parrotfish community provides a cost effective, simple and intuitive indicator of fishing effects. From an applied perspective it is easier to measure the attributes (e.g. body size, biomass, density) of the parrotfish communities with high precision than those of the snapper and grouper communities because the latter are now rare across the region.

Coral reefs are highly complex systems affected by multiple stressors. Thus, when possible, the use of average parrotfish weight as an indicator of fishing effects should be accompanied and contrasted with as much independent information available on fishing pressure and other local stressors.



*Parrotfish are often caught by trap fishers.*

## HOW IS IT DONE?

Average parrotfish weight can be calculated using reef survey data that includes the species, abundance and length of parrotfishes. Using simple length-weight relationships from Fishbase ([www.fishbase.org](http://www.fishbase.org)), the weight of each fish can be calculated. These weights can then be averaged across all parrotfish species at a site to give an estimate of average parrotfish weight.



## FURTHER INFORMATION

Vallès H, Oxenford HA. 2014. Parrotfish Size: A Simple yet Useful Alternative Indicator of Fishing Effects on Caribbean Reefs? PLoS ONE 9(1): e86291. doi:10.1371/journal.pone.0086291. Available free at: [www.plosone.org](http://www.plosone.org)

## Understanding and managing invasive lionfish

*Lionfish caught with a pole spear being put into a storage device called a zookeeper.*



*Lionfish are now found on reefs throughout the Caribbean, often in large numbers.*

### THE EVIDENCE

Lionfish are a native species of the Indo-Pacific that have been accidentally introduced to the Caribbean. The first lionfish were spotted off the coast of Florida in 1985. From 2000 they started spreading rapidly across the Caribbean.

Two species of lionfish have been introduced to the Caribbean so far: the red lionfish, *Pterois volitans* and the devil firefish, *P. miles*. The two are indistinguishable without genetic analysis, but *P. miles* has only been found along the southeast coast of the USA and in the Bahamas. Both species are members of the scorpionfish family (Scorpaenidae), characterised by their venomous spines.

Lionfish have been very successful in their colonization of Caribbean reefs, where population densities can reach 400 lionfish per hectare; 15 times that of their native Indo-Pacific reefs. However, densities of lionfish are hugely variable both geographically and by habitat. Some parts of the Caribbean still appear to have relatively few lionfish on their reefs (e.g., the Grenadines), and some habitats, such as patch reefs, tend to acquire higher densities than exposed forereefs.



*Lionfish are extremely efficient and voracious predators, able to eat 10% of their body weight per day. Experiments in the Bahamas showed lionfish were able to reduce their prey abundance by 80% in just 5 weeks.*

*Lionfish prey on more than 50 species of reef fish. Important reef fishery species, such as groupers and snappers, are consumed by lionfish in their juvenile stage when they are small enough for a lionfish to eat. This is reducing the ability of these often overexploited species to recover. The same principle applies to parrotfish which are important algal grazers.*

*Further reductions in parrotfish numbers on reefs inhibits the ability of corals to recover as reefs become dominated by algae which reduced numbers of parrotfish are unable to control.*



*Lionfish caught at a derby in Curaçao.*

The high density and rapid spread of lionfish are likely due to a number of factors:

- **Few natural predators** – native predators (sharks, groupers, etc) appear to be reluctant to consume lionfish, though some predation has been reported.
- **Multiply quickly** – capable of producing over 2 million eggs per year, spawning multiple times throughout the year and reach sexual maturity at less than one year of age.
- **High diversity of prey consumed** – lionfish consume a wide variety and sizes of fish and crustaceans.
- **Spread quickly** – lionfish larvae are estimated to spend between 20 and 35 days drifting in the plankton. This is sufficient time for the larvae to disperse over large distances and colonise distant reefs.
- **Prey naïvete** – their natural camouflage, slow movement and use of flared fins to herd fish mean lionfish can confuse their prey which, in the Caribbean, have not encountered such methods before.
- **Wide habitat range** – lionfish have been found from depths of 300m to the surface and on coral reefs, in mangroves, river estuaries and sea grass beds.



*Lionfish on measuring board.*

#### FURTHER INFORMATION

Morris, J.A., Jr. (Ed.). 2012. Invasive Lionfish: A Guide to Control and Management. Gulf and Caribbean Fisheries Institute Special Publication Series Number 1, Marathon, Florida, USA. 113 pp. Available online at: <http://lionfish.gcfi.org/manual/>

Mumby PJ, Harborne AR, Brumbaugh DR. 2011. Grouper as a natural biocontrol of invasive lionfish. PLoS ONE 6(6) e21510. Available free online at: [www.plosone.org](http://www.plosone.org)

## MANAGEMENT IMPLICATIONS

Lionfish are here to stay on Caribbean reefs, but management actions can help alleviate some of the problems. Management options for lionfish will depend on the resources available but might include three components:

### Education and awareness

Campaigns to promote understanding lionfish and the impacts they have on reefs can help to reinforce the management of lionfish in a number of ways:

- Reduce risk of people being stung and injured by lionfish.
- Increase support for other management measures.
- Raise awareness of the damaging effects lionfish have on the ecosystem.
- Mobilize support for removal programmes, particularly amongst divers and dive shops.
- Encourage consumption of lionfish.
- Prevent further introductions of invasive species, including additional lionfish.

### Removal

Where the density and size of large-bodied grouper is high – after 30 years protection – evidence exists that lionfish densities are relatively low on outer forereefs. However, 99% of Caribbean reefs lack the levels of grouper found on these reefs so grouper are unlikely to serve as a form of biocontrol (Mumby et al 2011). The only ways at present to control lionfish numbers is by active removal. This is normally done by scuba divers using adapted pole spears and sometimes nets or bags. Removal efforts have only a limited effect on lionfish numbers as populations will always be replenished from other reef areas and removal of all lionfish even at a small scale is practically impossible. However sustained local removal efforts can help reduce lionfish numbers on local reefs, thereby reducing their effect on the local reef ecosystem. It is important that removal programs do not harm the very reefs they are trying to conserve hence divers must take no other fish except lionfish and should not damage the reef while hunting for lionfish. Diver safety should also be stressed. To ensure rules are followed, some managers require that divers wishing to hunt lionfish are registered and undergo a training program. Removal of lionfish through the involvement of recreational divers has been effective in places such as Bonaire and the Florida Keys. Derbies are organized where a day or weekend of lionfish hunting and events take place, not only removing large numbers of lionfish from the reefs but also encouraging awareness of the scale of the problem. Consumption of lionfish is also being promoted in many places as they are seen as a sustainable and 'reef-friendly' food source.

### Monitoring

Monitoring of lionfish can determine the spread of lionfish on local reefs and the efficacy of any removal programs as well aiding in their improvement, e.g. removal efforts can be targeted on reefs where lionfish are most abundant. Commonly used surveys methods such as AGRRA, REEF and Reef Check already include lionfish in their protocols. Other innovative methods of monitoring include using data from recreational divers; Bonaire has a website devoted to mapping of lionfish around the island using volunteer submitted data:

[www.lionfishcontrol.org/](http://www.lionfishcontrol.org/)

# Managing parrotfish harvesting with habitat protection zones

Stoplight parrotfish  
(*Sparisoma viride*).

## THE EVIDENCE

In practical terms, there are two major foreereef habitat types: 'Orbicella (previously *Montastraea*) reef' and 'gorgonian plain'. The *Orbicella* reef is structurally complex, high in biodiversity, sustains large parrotfish populations and is where much of the 'reef-building' takes place. Gorgonian plains, in contrast, are relatively featureless flat pavements dominated by gorgonians (e.g. sea fans, whips and rods). *Orbicella* reefs require high levels of parrotfish grazing to help keep macroalgal cover in check. In contrast, data from Belize and the Bahamas showed no relationship between parrotfish biomass and macroalgal cover in gorgonian plain habitats, suggesting that algal growth in this habitat is controlled by other mechanisms such as wave exposure.

## THE APPROACH

The creation of HPZs that cover *Orbicella* reefs would help maintain good fish habitat for a host of fisheries species by protecting parrotfish where they are most needed. Harvesting of parrotfish would be allowed on gorgonian plains where parrotfish do not appear to play such an important role as grazers and habitat damage due to fishing is less likely due to the featureless nature of the plains. Such a compromise would allow fishers to continue harvesting parrotfish and fisheries management could focus on sustaining the fishery on the gorgonian plains. The total area of gorgonian plain often dwarfs that of *Orbicella* reef, implying that many areas would be fished as usual.

## THE ISSUE



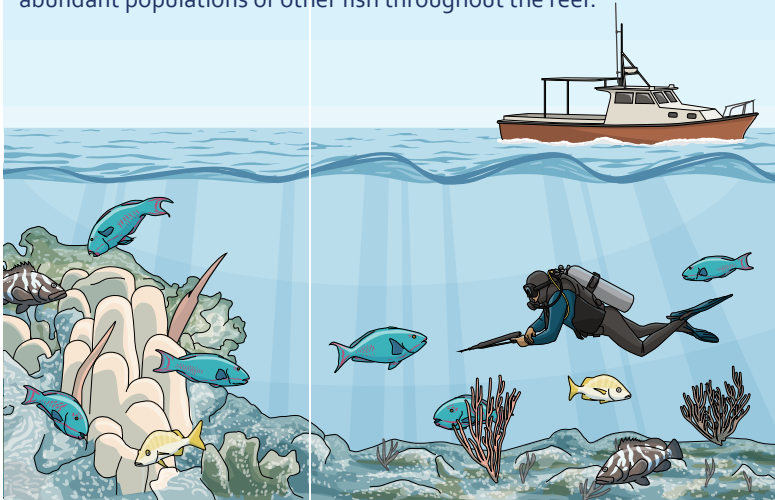
Parrotfish are an important fishery in many parts of the Caribbean and as populations of preferred fishery species such as groupers and snappers have declined, there has been a tendency for fishers to shift increasingly towards targeting lower value herbivorous fishes such as parrotfish. Fishing of parrotfish also occurs when fish traps are used, even if parrotfish are not the target species. However, sustainable fisheries – as well as other ecosystem services – require a healthy and structurally complex reef habitat which parrotfish play an important role in maintaining through their function as grazers of macroalgae.

To maximise the quality of reef habitat for continued fisheries, the best option to consider is a complete ban on herbivore fisheries. However, in areas where fishers are highly dependent on parrotfish, an alternative management strategy is needed that minimises impacts on reefs while still permitting fishing.

One option is to declare 'Habitat protection zones (HPZs)' that protect parrotfishes (while allowing continued exploitation of other species) on the reef habitats where their function as grazers is most needed. Fishing of parrotfish would continue in habitats where their grazing is less important.

## Managing Parrotfish Fisheries in the Caribbean

Protecting these animals on one part of the reef may allow for abundant populations of other fish throughout the reef.



### Orbicella reef

Complex, massive corals. Strong relationship between parrotfish abundance and algal cover. Low wave exposure relative to the gorgonian plain. Fishing for parrotfish prohibited, but allowed for other species.

### Gorgonian plain

Flat and few corals. No strong relationship between parrotfish and algal cover. More extensive than the Orbicella reef areas. Fishing for parrotfish allowed.



## HOW IS IT DONE?

*Orbicella* reef and gorgonian plains can be mapped using a variety of methods including the use of high resolution airborne images, boat-based acoustic surveys of seabed roughness or mapping of wave exposure. Managers may already have habitat maps of reefs that would allow mapping of the two habitat types. These maps can then be used to set HPZs encompassing *Orbicella* reef areas. Inevitably there will be some overlap between the two habitat types and zoning plans will have to find a compromise between protection of the maximum amount of *Orbicella* reef and the complexity of the resulting zoning plan.

To enforce the HPZs, three systems are possible: (1) direct enforcement using patrol boats; (2) bans of fish traps in HPZs, (3) indirect monitoring of fishing vessels through the use of a high-resolution monitoring system such as automated identification systems (AIS). AIS is a high resolution vessel monitoring system. If all fishing vessels had such a system installed and regulations stated that parrotfish cannot be caught on fishing trips that enter a HPZ, the AIS system could be used to check unambiguously if landed parrotfish could have been caught in an HPZ. In practice, fishers would have to decide whether to fish the HPZ on a given day and if they do, then the harvest of parrotfish outside the HPZ would not be feasible on that trip. If parrotfish were targeted on a given day then the HPZ would have to be avoided. If fishing was conducted outside the HPZ but no parrotfish were caught then other species could be targeted in the HPZ on the same trip.

## MANAGEMENT IMPLICATIONS

Ecosystem-based management of fisheries has been widely endorsed for its principle of sustainable fisheries management based on maintaining ecosystem function. The habitat protection zones proposed here offer one more tool for ecosystem-based management of coral reef fisheries. By protecting structurally complex reef habitat managers will help maintain fisheries productivity, thereby balancing the needs of fisheries with those of a healthy coral reef ecosystem.

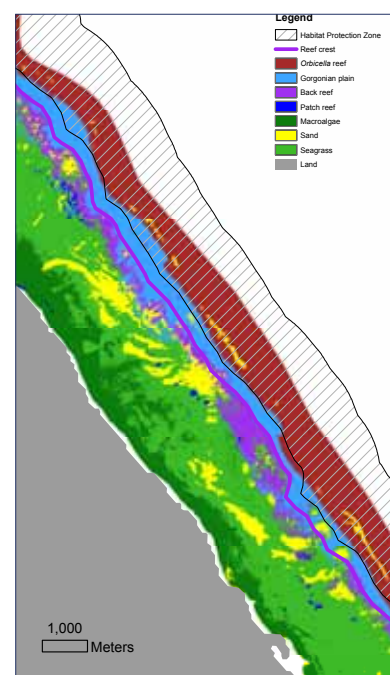
### FURTHER INFORMATION

Linking coral reef complexity p.71, Fisheries brief 7 p.90

Mumby PJ. 2014. Stratifying herbivore fisheries by habitat to avoid ecosystem overfishing of coral reefs. Fish and Fisheries. (doi: 10.1111/faf.12078)

Mapping of reef habitats can be done using the simple relationship described in Chollett & Mumby (2012) and wave exposure data available via the FORCE WebGIS, <http://force-project.eu/>

Chollett, I., Mumby, P., 2012. Predicting the distribution of *Montastrea* reefs using wave exposure. Coral Reefs 31, 493-503.



Map showing habitat protection zone and reef habitats.

## Using vessel monitoring system data for sustainable management of reef resources

Shrimp trawlers at dock.

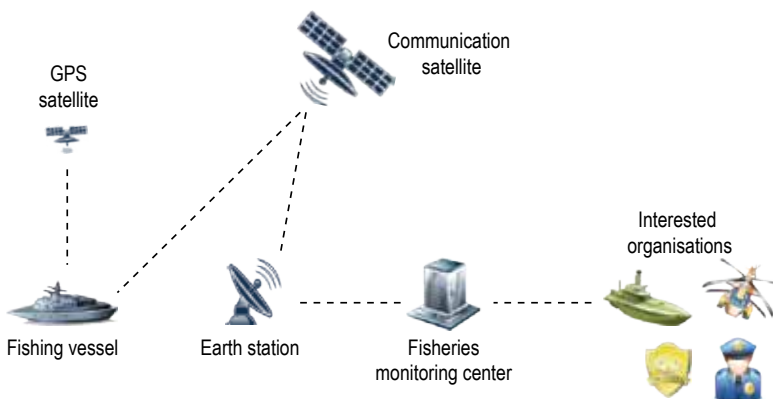
### THE EVIDENCE

A Vessel Monitoring System (VMS) is a satellite-based tracking system for monitoring in near real-time the location of vessels equipped with the technology. VMSs provide continuous information every hour on the position of fishing vessels, even when they are in port. This information can be transformed into outputs useful for resource management and conservation following simple GIS processing steps.

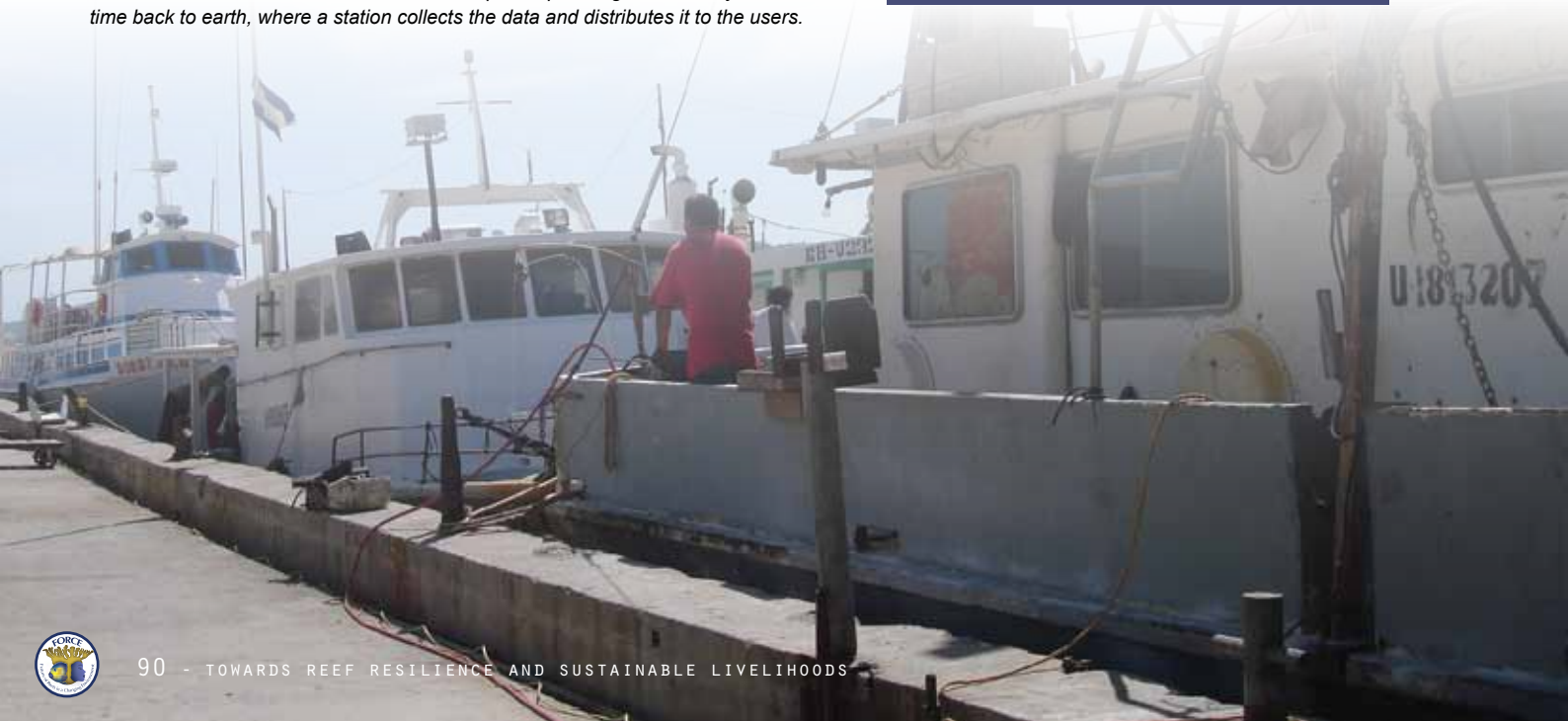
VMS is widely used in many countries throughout the world. In the Caribbean, Jamaica, Colombia, Honduras, Panama, Mexico and the USA have active VMS systems within their industrial fleets.

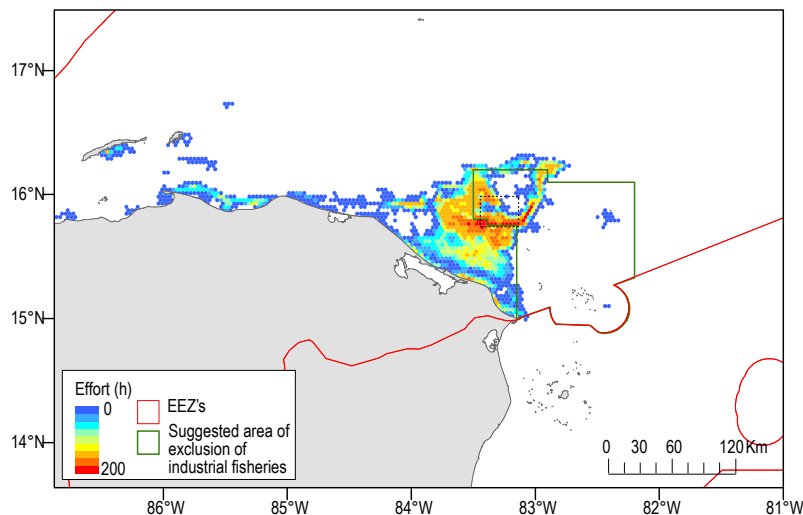
*Coral reefs serve as habitat for many commercially important species targeted by fisheries. Many people rely on reef resources as a source of income and for food. Well managed reefs can yield between 5 and 15 tons of fish and other seafood per square kilometre per year, however, more than 55% of the world's shallow reefs do not produce this potential as they are severely over-fished.*

*A number of management tools such as spatial (fishing zones) and temporal closures (harvesting seasons), as well as gear and species restrictions, are required. Enforcement of the first two of these management strategies is dependent on knowledge of the movement of fishing vessels. Vessel Monitoring System (VMS) provides relatively cheap, reliable and constant access to this information.*

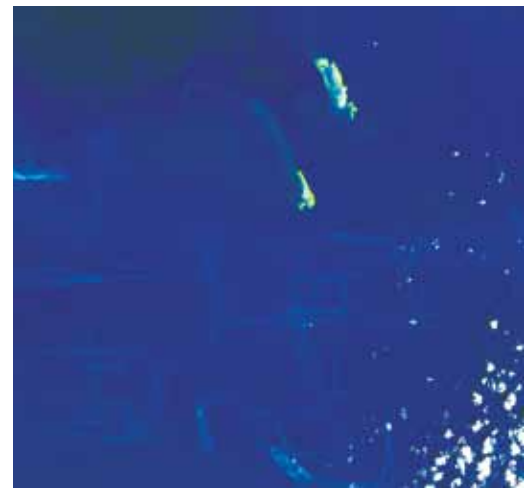


*VMS system: the boat has a VMS unit with an inbuilt Global Positioning System (GPS) receiver and an antenna on board. A satellite picks up the signal and relays it in real time back to earth, where a station collects the data and distributes it to the users.*





Map of fishing effort (hours) for shrimp fisheries boats in Honduras (2010-2012). This map collates information from 54 boats and 634,930 hourly records.



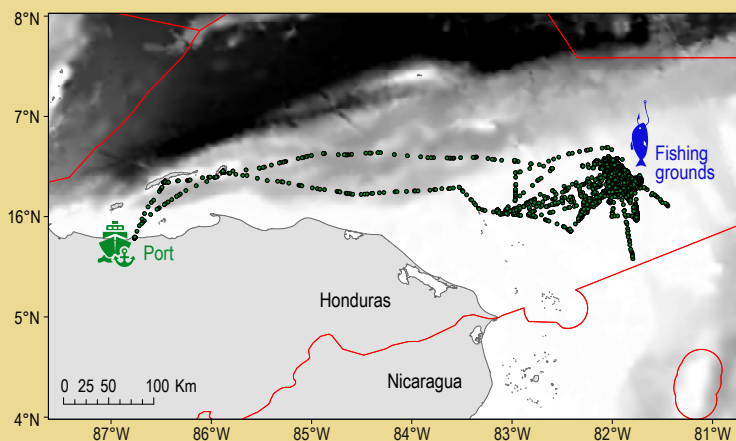
Satellite imagery showing scars left by trawling boats (in black dashed rectangle on map) inside the suggested area of exclusion of industrial fisheries.

## MANAGEMENT IMPLICATIONS

### VMS data can be used for a variety of management uses:

- Safety, used as an aid in search and rescue activities.
- Identification of poaching or incursions into protected waters.
- Identification of exceeded quota if the number of days at sea is limited.
- Identification of compliance with seasonal bans if there are temporal harvesting restrictions.
- Fisheries research and analysis by providing an estimation of spatial fishing effort.
- Maps of fishing effort can be used for reserve design. Maps can aid quantifying potential displacement of effort and spatial mobility of the fleet, or the fleet's ability to accommodate the management restriction and fish in other locations.

For enforcement activities to take place, government agencies need to monitor their data in real-time, in order to detect harmful or suspicious activity (i.e. wrongly entering into a marine reserve or patterns of movement that suggest prohibited fishing activity). In the Caribbean, installing the system is not the only priority; the data also needs to be made available to control centres.



VMS hourly positions of an industrial fishing boat in Honduras. Economic Exclusive Zones marked in red; bathymetry is shown in the background with darker colours showing deeper areas.

## FREQUENT ASKED QUESTIONS

### How much would this technology cost?

A VMS unit is about US \$1,500 and a daily network plan that guarantees the satellite transmission of the data is about US \$2 per day. However, many countries offer subsidies to vessels.

### What should I do if I need to monitor smaller vessels?

For smaller vessels a cheaper alternative is the Automatic Identification System (AIS) which does not use expensive satellite connection to transfer data. AIS records position more frequently and therefore is more useful to monitor smaller, faster vessels. However, set-up of the system requires a one-off investment and the building of a network of radio repeaters throughout the area to ensure full signal coverage.

### What about the monitoring of foreign vessels in my MPA?

Regulations can make the installation of VMS or AIS units mandatory to all vessels entering the park boundaries. The devices can be provided at rental cost, as is being planned in the Galapagos Marine Reserve.

## FURTHER INFORMATION

Chollett I, SJ Box, PJ Mumby. Displacement of fishing effort by an imminent MPA closure: when is it an issue? In preparation.

## Using connectivity for the transboundary management of reef species

Close-up, recently spawned eggs.

### THE EVIDENCE

Larval connectivity patterns of a variety of species can be understood using realistic models. These models incorporate maps of reef locations, detailed 3D models of ocean and coastal currents, and information on the biology of the species. An open-source model (the Connectivity Modeling System) incorporating all these complexities is now available to understand the connectivity patterns of different reef species within the Caribbean.

Models of larval dispersal efficiently predict real patterns in the field: for example, models for the most important Caribbean reef-builder, the boulder star coral *Orbicella annularis*, explain much of the genetic variability of these corals across the entire basin. Of course, many countries share connected resources – with larvae released in one country sustaining populations of fish and invertebrates in other countries downstream.

Coral spawning.

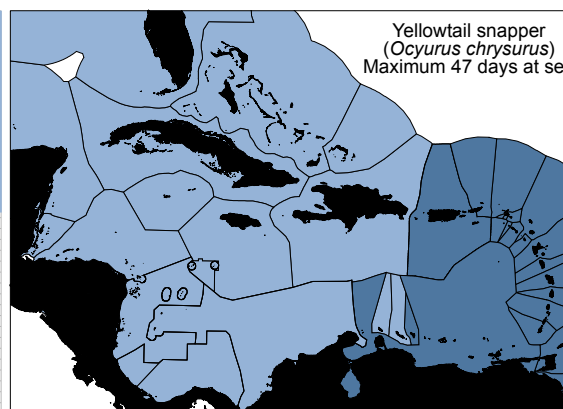
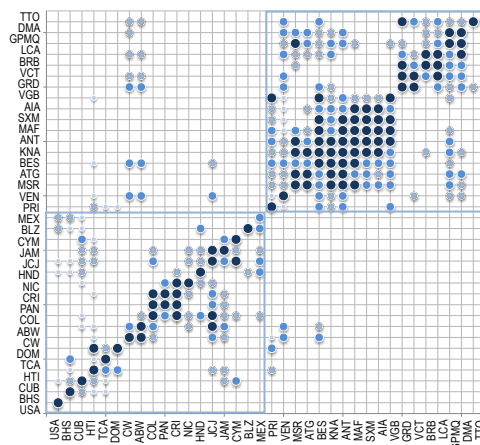
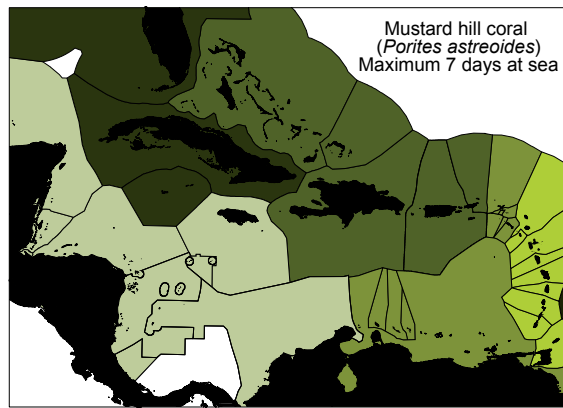
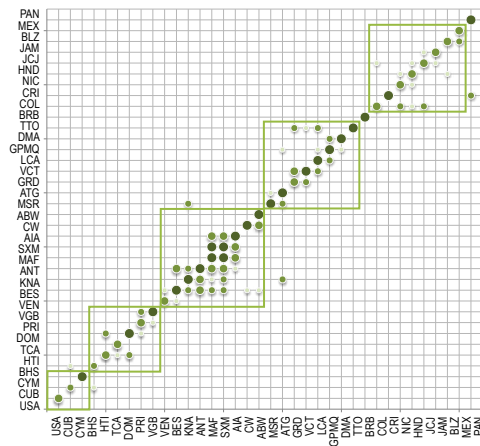
The relevance of transboundary issues for management and biodiversity conservation is being increasingly acknowledged. Worldwide, the number of transboundary protected areas has grown from 59 in the 1970's to 666 in 2001 to 3,043 in 2007.



*Setting boundaries and managing stocks of animals and plants is much easier on land than in the ocean. Since we cannot fence the sea, its inhabitants move freely among different areas, either as adults (by swimming or floating), or as offspring (larvae). Most marine organisms release larvae into the water column, where they are subjected to the prevailing currents, at times spending months in the water and covering perhaps hundreds of kilometres before finding a new home.*

*As a result, effective management of many marine species transcends international boundaries and requires international cooperation. Even if a country manages its own marine resources appropriately, the success or failure of its management will rely, in part, on the activities undertaken by neighbouring countries because of various organisms' transboundary connections.*

*To add an extra level of complexity to the issue, connectivity patterns differ among species. While some resources might be shared among neighbouring countries, others might not. Since resources for biodiversity conservation are limited, joint management activities and the development of networks, partnerships or regional coordinating institutions can enable the pooling of those resources to minimize duplication and maximise management benefits.*



United States (USA); The Bahamas (BHS); Cuba (CUB); Haiti (HTI); Turks & Caicos Is. (TCA); Dominican Republic (DOM); Puerto Rico (PRI); Venezuela (VEN); Montserrat (MSR); Antigua & Barbuda (ATG); Bonaire, Saint Eustatius and Saba (BES); St. Kitts & Nevis (KNA); Netherlands Antilles (ANT); Saint Martin (MAF); Saint Maarten (SXM); Anguilla (AIA); Virgin Islands, British (VGB); Grenada (GRD); Saint Vincent and the Grenadines (VCT); Barbados (BRB); St. Lucia (LCA); Guadeloupe-Martinique (GPMQ); Dominica (DMA); Trinidad & Tobago (TTO); Curacao (CW); Aruba (ABW); Colombia (COL); Panama (PAN); Costa Rica (CRI); Nicaragua (NIC); Honduras (HND); Joint regime Colombia/Jamaica (JCJ); Jamaica (JAM); Cayman Is. (CYM); Belize (BLZ); Mexico (MEX).

Connectivity matrices and possible transboundary management units for two reef species with contrasting biology. Connectivity matrices show the average proportion of larvae migrating from one country to another. Larvae originate from the left (rows) and settle at the bottom (column). Domestic connectivity (larvae that settled in their nation of origin) follows the diagonal. The strength of connections (size and colour of the bubbles) among sites is represented by five quantiles. This information can be used to categorize the Caribbean into management units which are more strongly connected within the units than among the units. To achieve this we used the clustering method of Girvan-Newman and the maximum modularity score to define the optimal partitions.

## MANAGEMENT IMPLICATIONS

Management plans focusing on particular species would look at their specific connectivity patterns to identify those species that will benefit from a transboundary conservation approach. The larvae of some species don't spend much time in the water column and so tend to stay in the waters of their home country, limiting the benefits of a transboundary approach. On the other hand, the management of species whose larvae spend a long time in the water column will need wide collaborative efforts.

Connectivity matrices showing where the larvae originate and where they go can help identify the best country groupings for transboundary management efforts, where cooperation could improve conservation outcomes. For example, for the coral *Porites astreoides*, connectivity patterns suggest at least 5 management units (or country groupings), while for yellowtail snapper, *Ocyurus chrysurus*, with widely dispersed larvae, only two management units might be required.

There are large disparities between larval imports and exports among countries. Maintaining the health of reefs and stocks of species in the regions or areas that contribute disproportionately to the Caribbean larval pool should be an international priority. For example, for yellowtail snapper, Montserrat supplies larvae to 12 countries and receives larvae from 9.

This does not reduce the importance of local reef management. Even if larvae can spend long periods in the water column, an important amount of larvae from each marine species stay within their home reef, which demonstrates that there is value in focusing on local conservation plans if transboundary approaches are not feasible at this stage.

## FURTHER INFORMATION

Kough AS, Paris CB, Butler MJ IV (2013) Larval Connectivity and the International Management of Fisheries. PLoS ONE 8(6): e64970

Paris CB, Helgers J, van Sebille E, Srinivasan A (2013) Connectivity Modeling System: A probabilistic modeling tool for the multi-scale tracking of biotic and abiotic variability in the ocean. Environmental Modelling and Software. 42: 47-54

Holstein D, Paris CB, Mumby PJ (2014) Consistency and inconsistency in multispecies population network dynamics of coral reef ecosystems. Marine Ecology Progress Series. 499: 1-18.

# Ecosystem Services and their Value



*Ecosystem services are vital to life. Clean air and water as well as the food we eat are all services which are provided by the natural functioning of ecosystems. Countries with coral reefs are often highly dependent on the services the reefs provide such as dive tourism, fishing and coastal protection. In the Caribbean, these three services alone are worth more than US\$3 billion annually and are important to the livelihoods of many communities. Failing to understand the value of ecosystem services can result in poor planning and decision making. Many methods exist for valuing ecosystem services and these are introduced within this chapter. For reef managers, valuations of ecosystem services can be useful in a number of different ways, principally for raising awareness of the value of reefs; to influence decision making and policies; in the calculation of compensation for damage to reefs; and to create sustainable financing schemes, such as marine park fees. Several valuation studies of coral reefs in Caribbean countries have already been conducted with the results being used to improve outcomes for both the reefs and the people who depend on them. Ecosystem services valuations are likely to play an increasingly significant role in policy decisions and planning and hence are an important tool for reef managers.*



Dive boat in Honduras.

## ECOSYSTEM SERVICES

The natural functioning of ecosystems provides many services to us as human beings that we often take for granted. At the most basic level, the air we breathe and the food we eat are ecosystem services. Four broad categories of ecosystem services are widely used (Millennium Ecosystem Assessment Board 2005):



- Provisioning services – these are the products that humans harvest and consume such as food, fresh water, wood and oil.
- Regulating services – these services control the environment, providing protection from floods and droughts and regulation of the climate.
- Cultural services – aesthetic, spiritual, educational, recreational and tourism services are all included: those services that improve our cultural wellbeing.
- Supporting services – the essential services that support all ecosystems and thereby the provision of the three categories above. Examples are: primary production, nutrient dispersal and soil formation.

The UN Millennium Ecosystem Assessment found that two-thirds of ecosystem services worldwide are in decline which is having a negative effect on the well-being of the people who depend on them (Millennium Ecosystem Assessment Board 2005). As the world population continues to grow from 7.2 billion today to a predicted population of more than 9 billion by 2050 (UN-DESA 2013), increasing demands and pressures are being put on ecosystem services. These demands are causing further degradation and loss of the very services we are trying to exploit. From food to nutrient cycling, ecosystem services underpin human life. Yet, until recently their value had not been properly considered.

*Local people enjoy weekends on the beach.*



*Fishing is one important provisioning service from reefs.*

### Valuing ecosystem services

Whether the question is to develop a natural landscape in order to increase tourism or to protect a natural area, we implicitly put a value on nature by looking at the services that are provided by the natural environment. The value of these services is traded-off against the benefits that can be gained by development. Economic valuation of ecosystem services allows us to quantify the benefits they provide. This helps with understanding the effects of any changes in the supply of services on human well-being. Putting a monetary value on ecosystem services allows decision-makers to incorporate the true economic value of ecosystems and the environment into their decisions.

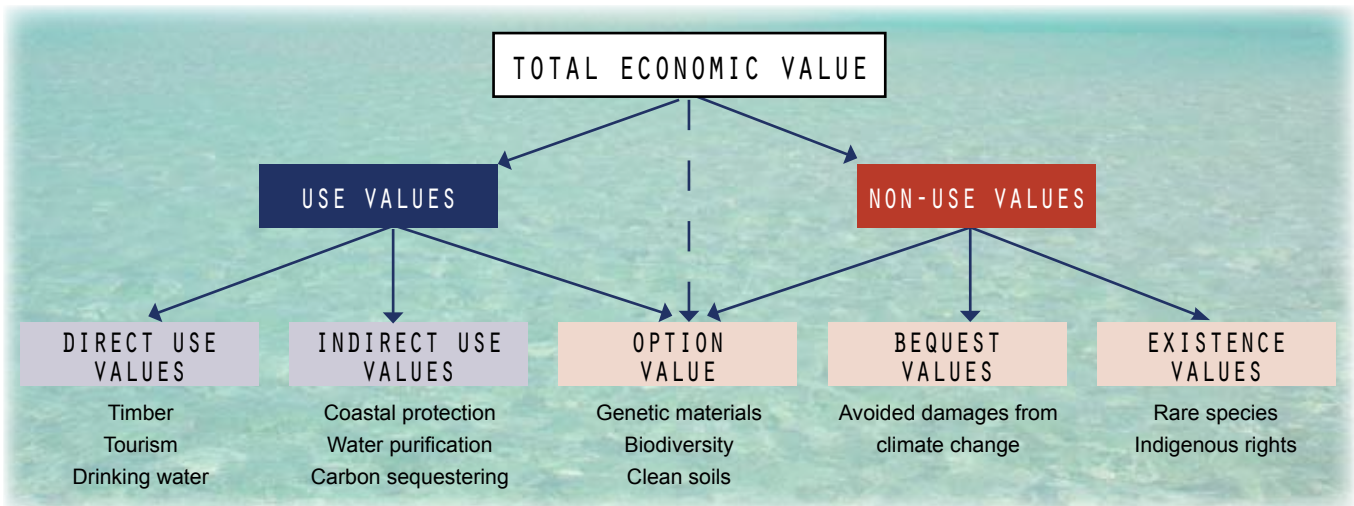
Some ecosystem services are relatively easy to put a value on, e.g. the value of fish from a coral reef can be seen in the price that people are willing to pay for them, although even this is more complicated than might at first seem, as fish might be worth more as an attraction for SCUBA divers than as food ([Services Briefs 1 p.108](#) and [Brief 2 p.110](#)). However many ecosystem services have no direct market value, e.g. clean air is a vital service, but we don't pay for it directly. For these services it is important that we try and value them in other ways so that they can be included in decision making that might affect the ability of the ecosystem to deliver the service. Where ecosystem services are not valued, they are frequently left out of the decision making process, which can result in poor development and planning decisions.

### Value concepts

To help understand and quantify the different values of ecosystems, the services can be split into different value categories. Total economic value (TEV) attempts to capture the value of services that we use ('use values'), such as food and water, as well as other 'non-use' values. Option values are considered a third group, since it is uncertain what sorts of services (use or non-use) might be provided by an ecosystem in the future.



## VALUES AND METHODS



### USE VALUES

Use values are divided between services that are used directly and ones that are used indirectly (regulate the provision of other services):

#### Direct use values

As the name suggests, are the values of services that are consumed directly. This can be in an extractive manner, when physical goods are taken from an ecosystem (e.g. wood from a forest as a building material). An ecosystem can also provide benefit in a non-extractive manner, like enjoying a dive on a coral reef or hiking in a forest. However, in order for a value to be categorized as a direct use value it is necessary for the consumer of the ecosystem service to be present and get some form of benefit. Direct use values are usually easiest to value, because people often pay to make use of the services they relate to.

#### Indirect use values

These are ecosystem services that generate benefits beyond the ecosystem being valued. Think of coral reefs or mangrove forests that protect villages from storms, or a rainforest that filters water for a city downstream. These services are often harder to value since the connection between the ecosystem service and the beneficiaries is often not as clear and the services are often not paid for directly.



Direct use values: urchin harvesting.

### NON-USE VALUES

Non-use values are the benefits that are provided by ecosystem services without making actual use of an ecosystem at the moment or in the future. There are three different types of non-use values:

#### Bequest value

This is based on the idea that we would like to preserve certain ecosystem services for the next generations. The willingness of many people to contribute to the reduction of global warming, although most of the effects are going to be felt by future generations, is an example of this category. Policy that aims to deal with long-term management or irreversible impacts on the natural environment is often based on bequest values.

#### Existence values

This is an attempt to capture the value of an ecosystem service simply continuing to exist. For example many people are very happy with the idea that endangered species are protected against extinction. Although most people will never visit the habitats and look at these species they are still willing to pay for the protection of these habitats and species. Just knowing that the species exists provides satisfaction.

#### Option value

It incorporates the fact that we are uncertain of the future values of an ecosystem. These are not use values because they are not derived from current use; nor are they necessarily non-use values because the services may have future use. Option values are therefore best classified as a separate ecosystem service value category that can be thought of as an insurance premium that people are willing to pay to preserve the supply of potential services in the future, e.g. preserving biodiversity for possible medical applications that we are not aware of yet.

The components of total economic value for ecosystem services.



Existence values: people are willing to pay for the protection of iconic species, such as whale sharks.



## CORAL REEF ECOSYSTEM SERVICES AND VALUES

Coral reefs are important providers of ecosystem services including tourism and recreation, fisheries and coastal protection. Putting a 'dollar value' on these services helps us to understand their importance for people's livelihoods and allows them to be incorporated into decision-making and policy. Services that are commonly valued for coral reefs are:

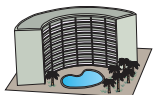
### Fishery value

Fisheries that are related to reefs can be important activities for both commercial, recreational and subsistence fishers. The value of the fishery is not solely related to the value of the fish sold or consumed because in many coastal communities fishing has social and cultural importance.



### Tourism value

Many islands and coastal zones in the tropics depend on the healthy reefs to attract tourists. Tourism can be a threat and a curse to the reefs. While it is important to maintain the quality



of the reefs, tourism also causes development and physical damage to this precious ecosystem. Think of construction, anchoring, human waste, inexperienced divers and snorkelers etc.



### Recreational value

Coral reefs provide a broad range of recreational activities to both residents and tourists (e.g. snorkelling, diving and beach activities).



### Coastal protection value

Coral reefs dissolve wave energy, which makes them important in protecting coastal areas from tropical storms and hurricanes. The healthier coral reefs are, the better they are at dissipating the waves and preventing physical damage to buildings and infrastructure. An important part of this value is mostly determined by the value of real estate and infrastructure that is protected by the reef ecosystem.



*Coral reefs are important providers of a wide range of ecosystem services.*

### Amenity value

People like the view of clean beaches and proximity to healthy coral reefs. This is why beachfront houses on nice coasts usually sell for significantly higher prices than houses in less appealing areas. To calculate these values, the hedonic pricing method is used when analyzing house prices or hotel room rates. With this methodology the added value of houses near healthy marine ecosystems are measured.



### Cultural values

Coral reefs often have a cultural importance to communities that live in the vicinity of coral reefs. In Saipan, for example, the appearance of migratory goatfish and juvenile rabbit fish are important events that bring families and friends closer together as they share in the catches. Less traditional, but very popular beach parties and barbeques also can be of cultural importance.



### Non-use values

As diverse ecosystems and habitats for many species, coral reefs provide important non-use values. The desire from people around the world to preserve coral reefs for future generations leads to bequest values. The existence value comes from the value that people put on the mere existence of these ecosystems. Voluntary donations by non-users to NGOs that are concerned with coral reef protections demonstrate the importance of these non-use values.



Ecosystem service values (US\$ millions)						References
	Tourism	Fishing	Shoreline protection	Amenity (house prices)	Local recreation and culture	
<b>Tobago</b>	100-130	0.8—1.3	18—33			Burke et al. 2008
<b>St Lucia</b>	160—194	0.4—0.7	28—50			Burke et al. 2008
<b>Belize</b>	135—176	13—14	120—180			Cooper et al. 2009
<b>US Virgin Islands</b>	103	3	7	37.1	51.1	van Beukering et al. 2011
<b>Bermuda</b>	405.9	4.9	265.9	6.8	36.5	Sarkis et al. 2010
<b>Turks and Caicos</b>	18.2	3.7	16.9			Conservation International 2008
<b>Caribbean</b>	2100	310	700—2200			Burke & Maidens 2004

*Ecosystem service values of Caribbean coral reefs.*



## VALUATION TECHNIQUES

The values of ecosystem services can be determined using several different methods, some of which can only be applied to certain groups of services. Primary valuation methods are characterized by the collection of data that is directly connected to the ecosystems being studied, e.g. price of fish in a market, willingness-to-pay for entry into a marine park. Primary valuation methods can be categorized into direct market price, revealed preference and stated preference methods. Secondary valuation methods use primary studies from

other locations to determine the value of the ecosystem services on which you are focusing. The values are transferred from one location or ecosystem to another. This method is normally referred to as value or benefit transfer.

### Selecting valuation techniques

There is no single valuation method that is the best option for every ecosystem, in every location, to value all services. Instead, it is important to consider what the goal of the study is and choose the appropriate valuation methods.

Valuation method	Approach	Applications	Examples (tropical coastal ecosystems)	Limitations
Direct market price	Observe prices paid in markets	Good and services that are traded in markets	Fish, Scuba diving and other reef tourism activities	Prices can be distorted, e.g. by subsidies. Many services not traded directly in markets.
Revealed preference	Similar to direct market price method in that it uses market prices, however the markets are complementary or substitutionary markets, not direct market prices.			
Net factor income	Revenues from sales of ecosystem services, minus cost of other inputs such as labour and materials	Ecosystems that provide an input into the production of a good or service that is sold on a market	Commercial fisheries supported by reefs	Over-estimates ecosystem value
Production-function	Estimates value of ecosystem service as input in production of marketed goods	Ecosystems that provide an input into the production of a good or service that is sold on a market	Commercial fisheries supported by reefs	Technically difficult High data requirements
Hedonic pricing	Estimate influence of environmental factors on marketed goods	Environmental characteristics that vary across goods (usually houses)	Value of reef incorporated into house prices	Technically difficult High data requirements
Travel cost	Estimate value of ecosystem based on time and money people spend getting to the ecosystem	Recreation sites	MPAs and other parks, reefs in general	Technically difficult High data requirements
Replacement cost	Estimate cost of replacing ecosystem service with man-made equivalent	Ecosystem services that have a man-made equivalent that could provide similar benefits	Coastal protection by mangroves/reefs	Often under-estimates value as man-made equivalents generally don't provide same benefits as ecosystem
Avoided cost	Estimate damage avoided due to ecosystem service	Ecosystem services that provide protection to property and infrastructure	Coastal protection by mangroves/reefs	Difficult to relate damage levels to ecosystem quality
Stated preference	Peoples willingness-to -pay (WTP) for ecosystem services or willingness-to-accept losses in these good and services is estimated by asking them hypothetical questions, e.g. how much would you be willing to pay for entrance to a marine park? Normally done using surveys.			
Contingent valuation	Ask people's willingness-to-pay for ecosystem services	Any ecosystem service	Entrance fees for MPAs, species loss	Bias in people's responses
Choice modelling	Similar to contingent valuation, except different combinations of services are offered as choices	Any ecosystem service	Tourism values of reefs	Bias in people's responses Technically difficult.

The selection of valuation techniques to value a specific ecosystem service will be dependent on a number of factors. Questions to ask are: is the service traded directly or indirectly in a market? Who are the important stakeholders that are affected by the ecosystem service? What are the financial resources that are available for the valuation study? and What is the availability of existing information on the value of similar resources?

### Using economic values in decision support applications

By developing scenarios, weighing different investments and evaluating or assessing policy plans, a valuation study is more likely to be used in the decision-making processes. The most suitable support tool or tools to use in the valuation study will depend upon the type of decision support application, and the information available.

When all the costs and benefits of a particular decision can be calculated the most logical tool to use is Cost-Benefit Analysis (CBA). This is the most commonly used tool for decision support. In a CBA all costs and benefits over a period of time are summed up and weighed against each other. The more the sum of benefits exceeds the sum of costs of a particular investment or intervention, the more favorable it is. Costs and benefits do not have to be expressed only in monetary terms; governments normally do CBA using costs and benefits to society, which includes welfare in a broader sense.

If there is a specific goal that should be reached and there are various ways to reach that goal it is easiest to perform a cost-effectiveness analysis (CEA). Benefits are determined upfront and the most effective way to reach the goal is evaluated.

If it is not possible to convert all societal costs and benefits into monetary terms, a multi-criteria analysis (MCA) can be used. In a MCA, you quantify your criteria in different



Shellfish souvenirs for sale in Honduras.



Industrial fishing boats, Honduras.

units or qualitative terms, similar to ranking. By determining the relative importance of the criteria it is possible to compare different alternatives based on these criteria.

**Total Economic Value (TEV):** All ecosystem services contribute to socio-economic welfare. The sum of these ecosystem services is defined as the TEV of that ecosystem and is normally expressed as a yearly value, e.g. the annual TEV of Bermuda's coral reefs based on values of six ecosystem services was US\$ 722 million (Sarkis et al. 2010). TEV can also be calculated for changes to the environment; for example, how much loss of a certain percentage of coral reef would cost in terms of economic value. It is important to understand that a TEV will fail to capture the total value of the ecosystem as there are some benefits that are simply too difficult to value properly, e.g. non-use values are frequently missed out due to the difficulty associated with understanding and valuing their benefits.

### Valuations tools available for use

There are several online, freely available tools or guides that can be used to help in ecosystem services valuations of coral reefs:

- The World Resource Institute provides a very clear explanation of their methods for performing valuations and a set of tools for use in valuation of coral reef fisheries, tourism and recreation and the economic impact of MPAS: [www.wri.org](http://www.wri.org)
- Another excellent guide is 'Valuing the Environment of Small Islands: An Environmental Economics Toolkit', which provides a step-by-step process for evaluation of ecosystem services, specific to small islands: [www.jncc.defra.gov.uk/](http://www.jncc.defra.gov.uk/)
- The Natural Capital Project offers a downloadable tool for ecosystem services evaluation called InVest. However only a few of the tools are tailored for the marine environment and considerable technical knowledge is required to use the tools: [www.naturalcapitalproject.org/](http://www.naturalcapitalproject.org/)

To effectively and rigorously conduct economic valuation of reefs, technical expertise will often be needed. Reef managers seeking to conduct ecosystem services evaluations might consider partnering with universities, NGOs or consultancies with knowledge and previous experience.



Value mapping shows the spatial distribution of ecosystem goods and services. Mapping the value of ecosystems has several purposes:

- Knowing which areas are most important in supplying ecosystem services helps to target conservation measures.
- It specifies the impact of threats. If threats are present in a value 'hotspot' then action might be prioritised.
- Different uses of ecosystems and development of natural areas often conflict with one another. By mapping ecosystem services it becomes clear in which areas there is conflict between stakeholders and a zoning plan can be developed (see Decision making).

Ecological economic modeling and climate change: Climate change is predicted to have increasingly negative impacts on coral reefs (Hoegh-Guldberg et al. 2007). However, few valuation studies have specifically addressed the impact of climate change on the supply of ecosystem services from coral reefs. Difficulties lie in understanding the complex responses of coral reefs to climate change and how those changes might then affect the ecosystem services they supply. For example, one recent study modelled the impacts of climate change on the recreational values for snorkeling and diving on coral reefs in three U.S. locations as well as the effects on existence values of the reefs (Lane et al. 2013). However, only the effects of coral bleaching on coral cover were included in the model, whereas climate change is likely to have multiple impacts on corals, including the effects of ocean acidification (Climate Change p.55). The study acknowledges the considerable number of factors not included in the model and the large uncertainty in many of the values used. Such modelling studies represent a first step to understanding the impacts of climate change on ecosystem services from coral reefs.

Protected areas planning  
Honduras



## MANAGEMENT USES OF VALUATION STUDIES

There are several reasons for conducting an economic valuation of ecosystem services. Five of the most common goals for economic valuation are:

- awareness raising and advocacy
- influence decision making and policies
- calculate damages for compensation
- create sustainable financing by identifying
- extractable revenues for environmental management.



Community meetings Honduras.

### Awareness raising

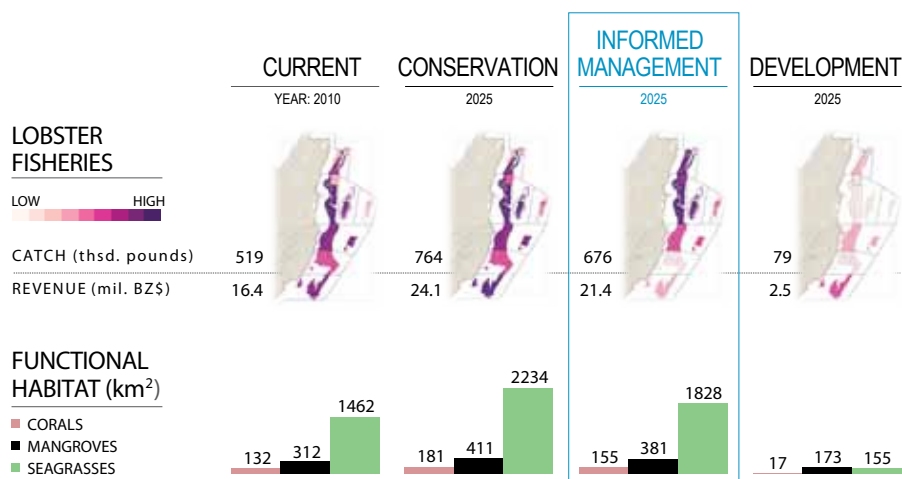
Putting values on the services that coral reefs provide helps raise awareness of how important reefs are for the economy and people's livelihoods. Ecosystem service valuations that have been carried out for a number of countries and services in the Caribbean demonstrate the economic importance of reefs to these countries and can help both decision makers and those involved in reef related activities understand the importance of the conservation of their reef resources (Bonaire case study p.105).

Ecosystem service valuations also highlight the role that coral reefs play in the livelihoods of local people. Many coral reefs are in small island developing states where the coral reefs are a significant source of income and food. Changes in the state of the reefs can cause considerable losses to those involved in reef based activities such as diving (Services Brief 1 p.108). and fishing (Services Brief 2 p.110). Valuation of these losses can help guide management decisions, leading to improved outcomes for the livelihoods of the people who depend on the reef.

### Decision making

Nature generally has a low priority in decision-making. To integrate the value of nature into management and policy decisions it is often necessary to have an estimate of the economic importance of ecosystems. Ecosystem services valuations provide such estimates and have been used in several Caribbean countries to influence policy decisions (Table page 103).

The use of scenarios and value maps can help decision makers understand the relative costs



and benefits of potential development or conservation plans. The Natural Capital Project in Belize developed value maps for three important ecosystem services: lobster fisheries, recreation and coastal protection, using data, computer models and expert opinion (Clarke et al. 2012). The changes in values by 2025 were then predicted for three different scenarios; conservation, development and compromise (which represented an informed management, balancing conservation and future development needs). The resulting maps will be used to help policy makers see the potential changes in ecosystem services under different

scenarios and balance the costs and benefits of development (Figure above).

Although valuations provide a monetary value of an ecosystem service, such values will never incorporate all values of ecosystems; there are some values that cannot be simply reduced to monetary terms. Valuations can therefore help guide policy but should not be seen as the total value of services provided or the only input into the planning process. This is particularly important in the case of some services which are particularly hard to value, such as the spiritual, religious and inspirational values of ecosystems.

Country	Study Site	Ecosystem	Ecosystem services valued	Policy influence of economic valuation	References
Belize	National-level	Coral reefs/ mangroves	Tourism/ fisheries/ shoreline protection	Supported action on multiple fronts, including (a) a landmark Supreme Court ruling to fine a ship owner an unprecedented and significant sum for a grounding on the Mesoamerican Reef; (b) the government's decision to enact a host of new fisheries regulations (a ban on bottom trawling, the full protection of parrotfish, and the protection of grouper spawning sites); and (c) a successful civil society campaign against offshore oil drilling.	(Cooper et al. 2009)
Dominican Republic	La Caleta Marine Reserve	Coral reefs	Dive tourism	Findings were used to justify a significant increase in user fees. Additional revenue has been used to help establish an aquatic center, a conservation fund to support park management, and a community fund to support local development projects.	(Wielgus et al. 2010)
Netherlands	Bonaire National Marine Park	Coral reefs	Dive tourism	Justified the Bonaire Marine Park's adoption (and later increase) of user fees—making it one of the few self-financed marine parks in the Caribbean.	(Dixon et al. 1993; Thur 2010; Uyarra et al. 2010; )
St. Maarten	Man of War Shoal Marine Park	Coral reefs	Tourism	Used by the government of St. Maarten to establish the Man of War Shoal Marine Park—the country's first national park. The valuation results are currently being used to sue for damages caused by the sinking of a boat inside the Man of War Shoal Marine Reserve.	(Bervoets 2010)
United States	Florida Keys National Marine Sanctuary	Coral reefs	Tourism	Established a schedule of escalating fines for injury to living coral based on the area of impact, resulting in the Florida Keys National Marine Sanctuary recovering millions of dollars for reef restoration after ship groundings.	(NOAA 2012)

*Selected coastal valuation success stories in the Caribbean.*



2003, M/V Kent Reliant grounded at the entrance to San Juan Harbor, Puerto Rico.

### Damage assessment

Valuation of ecosystem services can be used to justify claims for damages to an ecosystem. The claims include the cost to restore the natural resource to its original state, plus costs associated with the loss of ecosystem service function, because the ecosystem can rarely be returned to its exact original state. In the Florida Keys, economic valuation of the coral reefs has been used to make claims for damages due to ship groundings (NOAA 2012). Such claims have yielded millions of dollars to restore the damaged reefs. A note of caution should be added as successful restoration of reefs is often not possible due to the difficulties associated with reef restoration efforts and the fact that damages may have fundamentally altered the physical environment of the reef area.

Stakeholders in the damage assessment process can include the community, business and government level organisations. The ideal damage assessment should assess the lost or reduced benefits from the ecosystem services to all groups. Damage claims based on ecosystem services valuations are likely to become more common in court cases as valuations become more extensive and comprehensive.

Visitors' fees help maintain national parks in Bonaire.

### Sustainable Financing

Directly charging for the use of an ecosystem service offers one way of sustainably financing the management and conservation of ecosystems. A common example of this in the context of coral reefs is charging entrance fees for marine protected areas (MPAs). Bonaire National Marine Park (BNMP) is a frequently cited case study of how entrance fees can be used for the sustainable financing of a MPA. A willingness-to-pay (WTP) survey (*contingent valuation*, Table p.100) of visitors to Bonaire was conducted in 1991 and the results were used to help justify the introduction of a US \$10 admission fee for SCUBA divers in the park (Dixon et al. 1993; Thur 2010). This resulted in the park becoming self-funding by the end of 1992, with the money being used to fund conservation, monitoring and enforcement of park regulations. The admission charge for divers was raised to \$25 in 2005 based on the results of another WTP survey and the need to increase funds for management (Thur 2010). A charge of \$10 for other marine park users was also introduced at the same time. Other marine parks within the Caribbean have followed suit and used economic valuation studies to justify the introduction of user fees (Table p.103).



Surveys conducted by FORCE researchers revealed considerable WTP from visitors for higher abundances of large fish, as well as avoiding encounters with fishing gear (Brief 1). Such results can be used to justify fees for reef management and conservation programs.



# THE VALUE OF NATURE IN BONAIRE

The economy of Bonaire is highly dependent upon tourism, with fishing also playing a significant cultural role on the island. Both of these activities are highly dependent upon the healthy functioning of the ecosystems of the island. To gain a fuller understanding of the value of nature to Bonaire's economy and the wellbeing of the inhabitants, an economic valuation of the main ecosystem services was conducted, commissioned by the Dutch Ministry of Economic Affairs. The approach covered both terrestrial and marine ecosystems and more than 10 different ecosystem services were valued.

More than 1,500 people were surveyed, including 400 tourists, 65 fishermen, 400 local residents, and 800 citizens of the Netherlands. During the surveys the willingness of individuals to pay for the protection of nature in Bonaire was estimated, as well as mechanisms (e.g. user fees) through which such payments could be transferred.

The total economic value (TEV) of the ecosystem services valued in this study was US \$105 million per year. The results of this study gained considerable attention with an associated documentary shown regularly on TV in Bonaire and local newspapers and NGOs reporting and publicizing the findings. The study has helped obtain €10 million in funding from the Dutch government for the conservation of nature in the Dutch Caribbean (including Bonaire, Saba and St Eustatius). The non-use value has been used by WWF Netherlands to secure a 3-year conservation budget for the Caribbean Netherlands.

The Dutch Chamber of Parliament has cited the coastal protection valuation in debates regarding new construction projects in the Bonaire marine park. The ecosystem service values have been



used to create more insight for important decision-making.

*Kayaking in the mangroves in Bonaire.*

Analysis of different future scenarios for ecosystem services values provided clear evidence that it is more efficient to prevent damage than attempt to restore the environment, or in the words of the study: "an ounce of prevention is worth a pound of cure". With current threats unmanaged, the TEV of nature in Bonaire will decrease from US \$105 million today to around \$60 million in ten years and to less than \$40 million in 30 years.

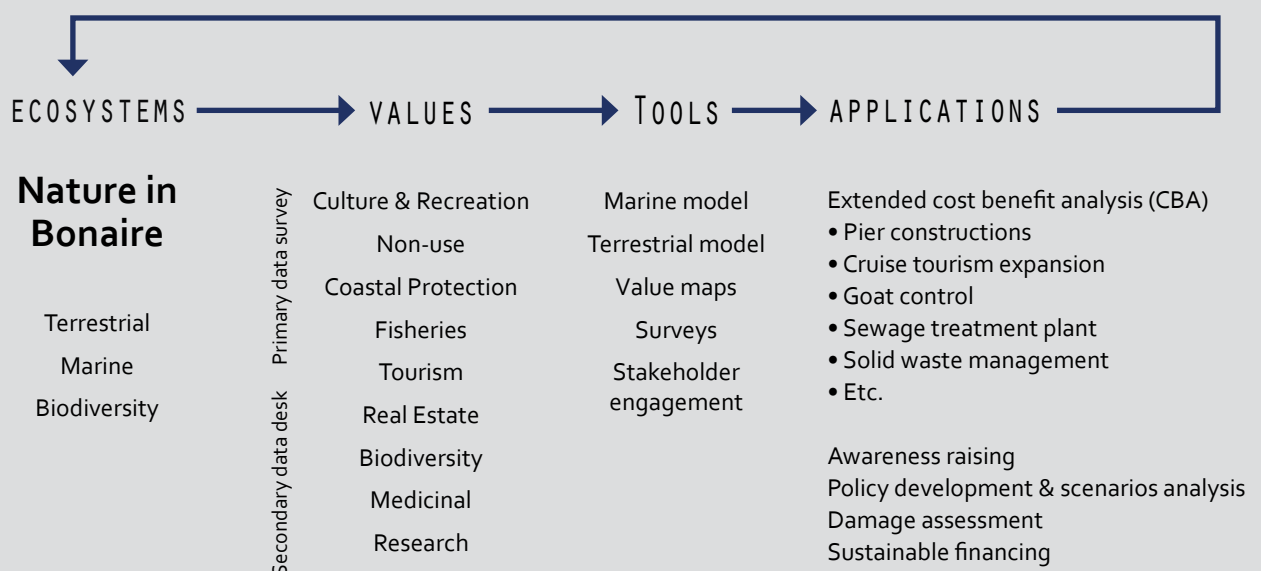
The value maps that have been produced for the study will most probably be used for the strategic environmental impact assessment in the coastal waters of Bonaire. The considerable impact of this study can be attributed in part to the media coverage and associated documentary as well as the accessible online reports and policy briefs. Engagement with stakeholders and their interest in the project helped ensure its success.



*Birds in Bonaire National Park.*

## FURTHER INFORMATION

What's Bonaire's nature worth? Policy Brief and reports available at [www.ivm.vu.nl](http://www.ivm.vu.nl)





**David Gill**

**CERMES, University of the West Indies**



*Coral reefs are extremely important for many reasons. We get a lot of goods and services from them. We commonly associate people such as fishermen and people in tourism from benefiting from reefs but we also benefit in other ways as well. They protect our shores and provide us with sandy beaches and a lot of space for recreation as well.*

*Yes, I have definitely noticed changes in coral reefs. One good example is the spiny sea urchin. When I was young, many, many times I would come home with spines in my feet from the beach and after about 5 years I wasn't getting any spines in my feet and also when I went snorkelling I wasn't seeing any of the long-spined urchins.*

**When I was young, many, many times I would come home with spines in my feet...**



#### **MY RESEARCH**

is looking at what is the economic value of reef fish – to the fishing industry and to the diving industry in the Caribbean.

1

Economic value of reef fishes to the dive tourism industry: the implications of reef fish decline



2

Potential economic impact of reef fish decline on Caribbean reef fisheries



## Economic value of reef fishes to the dive tourism industry: the implications of reef fish decline



*Every year, dive tourism contributes billions of dollars to Caribbean economies and funds marine conservation in many locations.*

*However, the coral reefs and associated fish species that attract millions of dive tourists each year are stressed from factors such as climate change and fishing. With the current financial downturn in global economies, consumers are more conscious of their spending and want more for their money. Lower quality reefs may cause conscientious consumers to go elsewhere to experience the quality of reefs they are willing to pay for. Areas with degraded reefs and declining fish populations could therefore experience significant losses due to a decrease in their share of the dive market.*

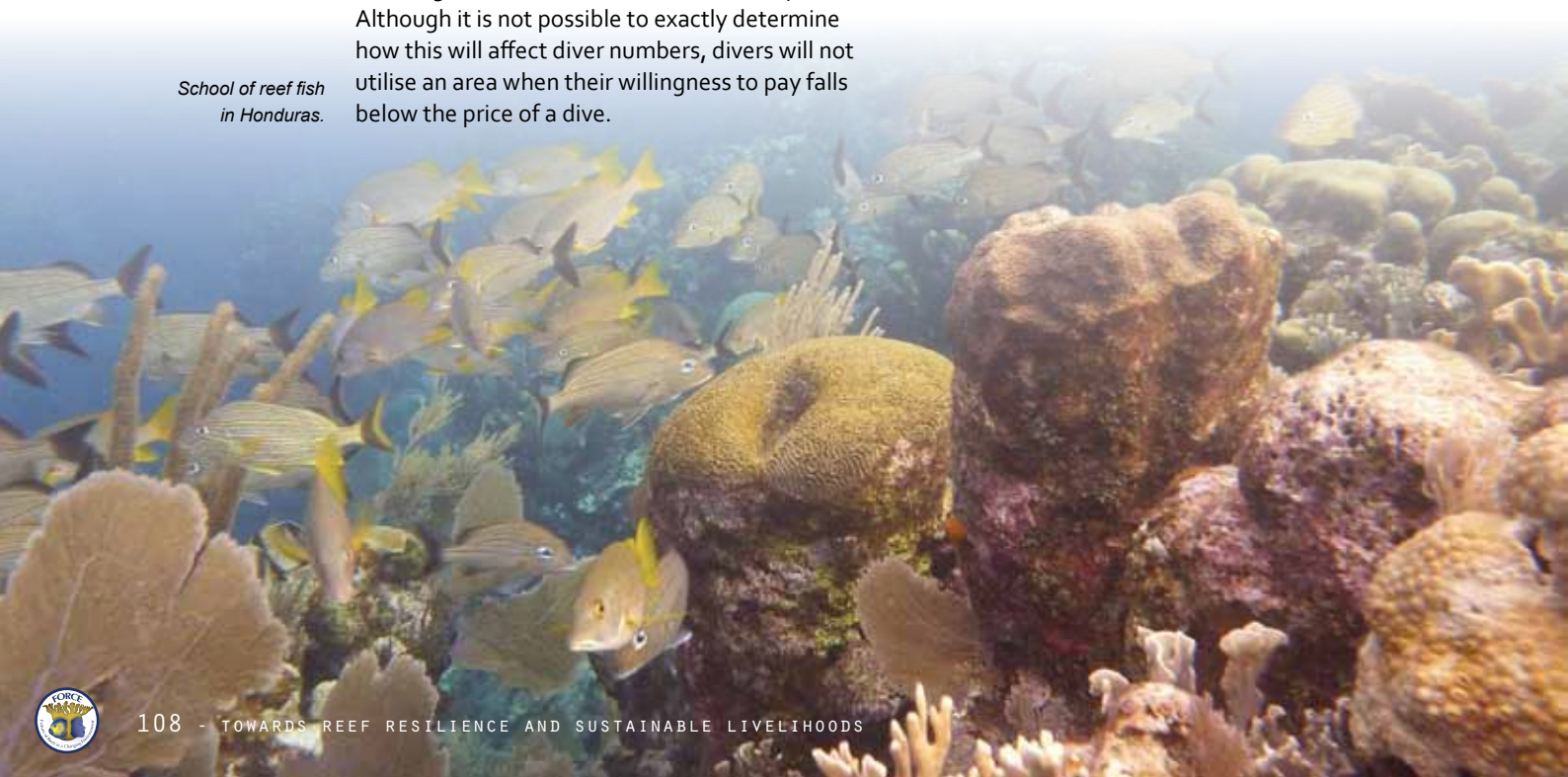
*Dive tourism is an important source of income for many Caribbean countries.*

### THE EVIDENCE

A large-scale survey of divers in Barbados, St. Kitts and Nevis and Honduras looked at their willingness to pay for dives with varying levels of fish life as well as to avoid encountering fishing/ fishing gear. Divers stated they would be willing to pay US\$51-\$79 more to dive with moderate numbers of large fish (10-25% of fish greater than 20cm) compared to current conditions (i.e. 1-10%). Further, divers were willing to pay US\$93-\$110 more to avoid diving with very few fish compared to current conditions. Although these values do not directly represent the price that can be charged for a dive trip, the results confirm that divers are willing to pay significant sums to see abundant and large fish life and that healthy reef fish communities are a very important component of the dive experience.

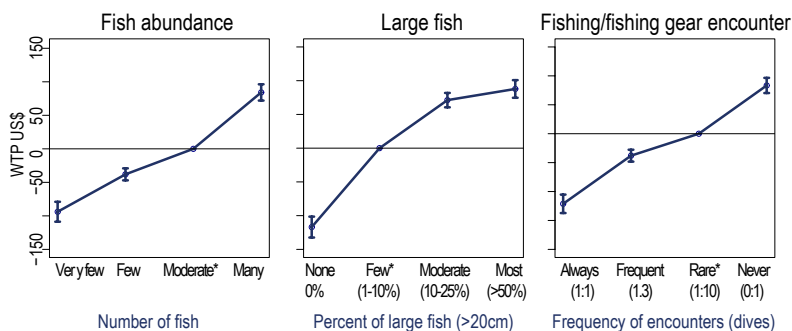
If nothing is done to stem the decline of the sizes and numbers of reef fish in the Caribbean, the losses to the dive tourism industry could be significant. For example, based on the number of divers in Barbados and St. Kitts and Nevis, annual losses of US\$1.2-2.1 million in diver consumer surplus (i.e. reductions in willingness to pay for diving) could be expected in each country. In the Bay Island sites (Honduras) with extremely high diver traffic, total losses could be as high as US\$7.6-\$12.2 million annually. Although it is not possible to exactly determine how this will affect diver numbers, divers will not utilise an area when their willingness to pay falls below the price of a dive.

*School of reef fish in Honduras.*





Divers willingness to pay (WTP in US dollars) for a two-dive package with varying numbers of fish, amount of large fish and fishing/fishing gear encounters, relative to the baseline/current conditions (average model with mean and standard errors). \* indicates current conditions.



## MANAGEMENT IMPLICATIONS

### Investment in conservation

With such potential losses from declines in reef fish, spending a portion of the potential lost value to ensure the sustainability of reef fish populations appears to be justified. If fish populations are sustained or even improved, divers will receive considerable satisfaction from these areas, increasing their likelihood of return.

### Investment in conservation and user fees

In order to fund conservation activities, some of the diver consumer surplus can be captured by charging user fees. For example, the operation of marine protected areas in Bonaire and Saba is almost entirely funded through user fees. Furthermore, in the current study, divers were willing to pay significant amounts to avoid fishing gear. It is therefore financially feasible to designate no fishing areas where entrance fees are charged. These no fishing areas are best chosen with some form of consensus from all marine users.



Tourism can provide a source of funding for marine reserves and management.

## FREQUENTLY ASKED QUESTIONS

### *Aren't divers just happy to dive in warm water?*

Although the dive market consists of many novice divers who may be less concerned about reef quality, more experienced divers spend more to visit higher quality sites. If your fish population degrades to the point where it is not worth their money (i.e. below their willingness to pay), they will go elsewhere to find better reefs. Better reefs gain a better reputation and more reputable reefs bring more divers, increasing revenue to local communities. This also applies to snorkeling and other underwater viewing activities.

### *How does dive tourism benefit the rest of the economy?*

The spill-over effect of dive tourism is tremendous. The average diver spends almost twice as much as the average tourist during their stay. In many areas, the presence of a strong dive industry has also promoted environmental awareness and involvement by local resource users.

### *From a fisher's point of view, how does it benefit me? Does this mean that I will have to stop fishing?*

Other studies have shown that protecting fish stocks in one area has had noticeable benefits to fishing on neighbouring reefs. The aim is not to rob fishers of their livelihood but to manage areas to improve the benefits to all stakeholders. Areas for SCUBA diving where fishing is not allowed can co-exist with and benefit zones with priority for fishers. Some jurisdictions have also created no-SCUBA areas where only fishing is permitted.

### *As a manager, what are the best ways that I can spend money based on these results?*

Fish abundance is closely linked to the quality of the habitat. Spending funds on reducing stressors to coral reefs such as fishing, pollution, and physical damage will help maintain the quality of the reef habitat that high fish populations are dependent upon. Fishing reduces the average size of fish on the reef. To see improvements in the overall size of fish, fisheries-related management should be a priority. As divers appear to be averse to seeing fishing activity/gear, designating separate recreational and fishing zones can improve the dive experience as well as reduce conflicts between user groups.

# Potential economic impact of reef fish decline on Caribbean reef fisheries

Reef fish catch.



Fisherman with catch in Honduras.

## THE EVIDENCE

Socioeconomic and fisheries data were collected from over 215 commercial fishers through face to face interviews and local focus groups in nine coastal communities in three countries (St. Kitts and Nevis, the Bay Islands [Honduras] and Barbados). In addition to collecting data on their fishing practices, fishers were also asked if they would change their fishing behaviour if there were changes in the numbers and sizes of fish in their catch in the future.

For the nine study sites, estimated annual net revenues from reef-associated fishing ranged from US\$0.03-0.95 million (PPP dollars) with average net revenues per fisher ranging from US\$2,549-26,489 per year.

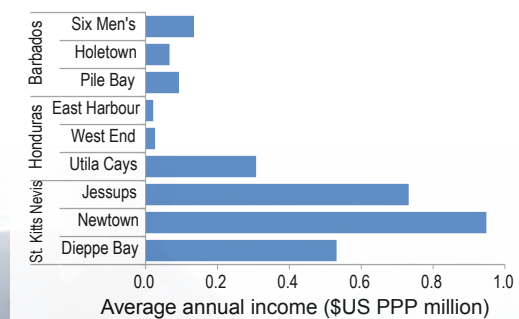
Fishers gave varied responses to questions regarding hypothetical changes in the size and quantity of fish in their catch but overall, many fishers stated that they would not change their fishing effort.

*Estimated average annual net revenue from reef-associated fishing (total per site) based on interviews with commercial reef fishers in nine coastal communities in St. Kitts and Nevis, the Bay Islands (Honduras) and Barbados.*

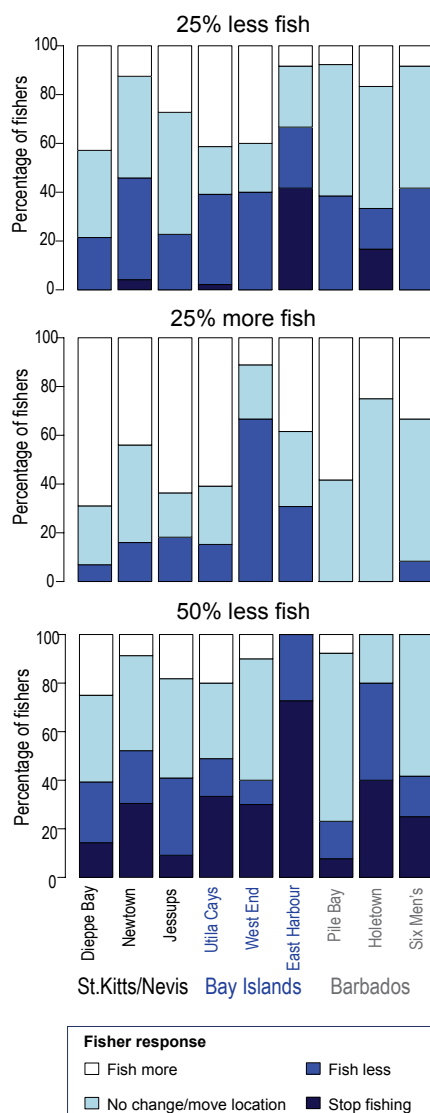


*In many coastal communities in the Caribbean, reef fishing represents a significant source of revenue and nutrition. However, recent declines in reef fish populations as a result of unsustainable fishing and habitat degradation threaten the livelihoods of those that depend on this fishery.*

*Another major problem is the limited availability of data on reef fishing and other small-scale fisheries, thus affecting the ability of policy makers to make informed management decisions.*



With a scenario of increases in the numbers and sizes of fish in their catch, most fishers stated that they would fish more while others stated that they could fish less and get the same amount of fish. A scenario involving a drastic decline (50%) in the number of fish, however, led to 27% of fishers stating that they would stop fishing altogether, which could translate into economic losses due to lower catch and fishers leaving the fishery. Estimated losses in revenue at each site ranged from US\$17,246 in West End, Honduras to US\$618,349 in Newtown, St Kitts and Nevis. Similarly, with a 50% reduction in the mean size of fish in catch, 20% of fishers stated they would stop fishing, translating into potential economic losses ranging from US\$15,919 (West End, Honduras) to US\$632,090 (Newtown, St Kitts and Nevis). Importantly, these scenarios are consistent with predictions for future fish productivity if reef habitat is allowed to flatten (Fisheries: Linking coral reef complexity p.71).



*Hypothetical responses of commercial reef fishers interviewed in St. Kitts and Nevis, the Bay Islands (Honduras) and Barbados to scenarios relating to changes in the size and abundance of fish in their catch five years in the future.*

## MANAGEMENT IMPLICATIONS

The results show that reef fishing is a significant revenue-generator in Caribbean coastal communities. Given that many rely on this fishery for income and nutrition, there is justification for substantial investment in the conservation of reef fish resources to avoid significant social, economic and ecological losses in the region.

### Three options available to managers are:

#### Business as usual

The current regional trends of declining catch per unit effort and decreased abundance of high value species, such as lobsters, snapper and grouper (both on reef and in catch), indicate that if nothing is done to stem these declines, considerable economic and societal losses should be expected in association with declining reef health.

#### Restrict fishing effort

Many areas in the Caribbean with restricted fishing zones have seen an increase in the numbers and sizes of fish on the reef. To see greater benefits, the size and location of restricted fishing areas and the enforcement capacity of the managing organisation need to be considered in the planning process. Connectivity of marine species between protected areas should also be considered to improve the outcomes of all protected areas in a network (Fisheries Brief 8 p.92).

#### Ecosystem-based management approach

The results indicate that declining fish stocks could cause a reduction in fishing pressure, with differing responses dependent on the site, even within a country. Although this will result in significant economic and societal losses, a reduction in fishing effort would be welcomed by many managers as this could allow fish stocks time to recover. Nevertheless, reduced fishing pressure alone does not address all the driving factors behind reef fish decline, including poor water quality from land based activities and reef damage.

On the other hand, with improvements in reef fish catch, many fishers indicated that they would increase fishing effort. Therefore, if a successful MPA were to increase fish biomass outside of its borders, or if stocks were to improve after a closed season, these effects may quickly be offset by increased fishing pressure. A similar response can be seen in the intensive fishing that occurs at the beginning of open seasons when healthy, recovered stocks are rapidly overfished within the first few days.

All of these factors highlight the need for a holistic, ecosystem based approach to cope with changes in reef fish resources and user behaviour. To reduce the probability of overexploitation after stock improvements, fishing effort and the entry of new fishers could be limited during the opening of a season or in areas surrounding replenishment zones. Further, responding to poverty and resilience needs by supporting livelihood diversification and exploring more sustainable fisheries practices to meet local food demand are other solutions that could be considered.

# Governance

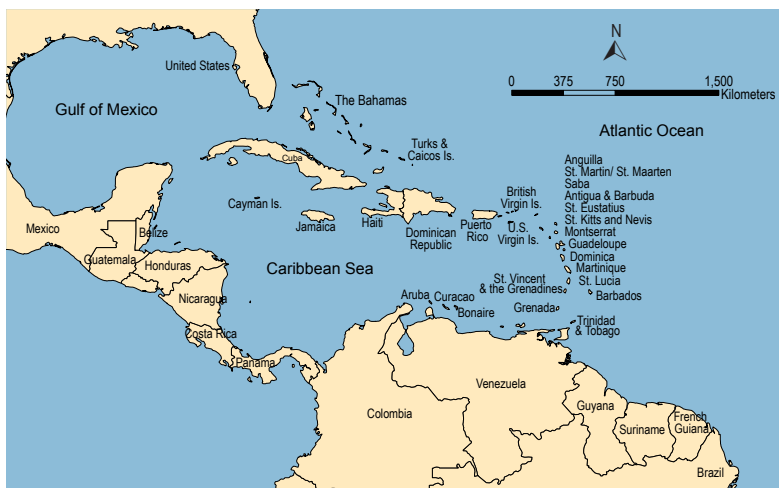


*The Wider Caribbean Region (WCR) consists of a diverse group of countries connected through the waters of the Caribbean Sea and the North Brazil Current. Marine resources such as fish move freely across national boundaries and the effects of land and marine-based pollution from one country can easily impact neighbouring nations. Coral reef based tourism and fishing both play a significant role in the economies of many Caribbean nations. Marine resources also play an important cultural and spiritual role in the lives of many people within the region. Cooperation to ensure the sustainability of marine resources is therefore in the interest of all nations. There are already many organisations dealing with marine resource governance within the WCR and the Caribbean Large Marine Ecosystem (CLME) project, briefly introduced here, aims to improve engagement and coordination among organisations. Improved governance across all levels, from local to global, is vital to ensuring improved management of coral reefs and other marine resources throughout the region.*



Marine Park Office in Roatan.

## GEOPOLITICS IN THE WIDER CARIBBEAN REGION



*Countries of the Wider Caribbean Region.*

The Wider Caribbean Region is one of the most geopolitically complex regions in the world due to the high diversity of cultures, languages, sizes of states and levels of development of countries within the region. Large continental countries, such as Colombia, are represented, as well as small island states, such as St Kitts and Nevis, with development levels ranging from some of the world's most developed countries, such as the USA, to some of the least developed, such as Haiti. In total there are eighteen small island developing states within the WCR. The region as a whole is strongly dependent on marine resources for the tourism and fishing industries which make up a large part of many countries' economies.

Many of the marine resources within the region are shared and/ or connected: fish populations move across the marine boundaries between countries; corals and reef fish produce larvae that travel freely across international boundaries. Marine transportation connects the region as large amounts of both goods and passengers (e.g. cruise ships) pass through the territorial waters of many nations. The Panama Canal is the main focus of international shipping with 5% of the world's trade passing through it.

*Beach tourism in the Caribbean.*

Fishing and tourism are the main sources of income in many of the nations within the WCR. The cultural, recreational and spiritual value of marine resources is integral to the lives of many within the Caribbean.

The impacts humans have on marine resources are frequently felt across boundaries, for example pollution and land-based run-off can easily travel across the waters of several nations. The high density of small states within some areas of the region makes cooperation particularly important, although this is complicated due to disputes over exclusive economic zones (Blake & Campbell 2007; Perez 2009).

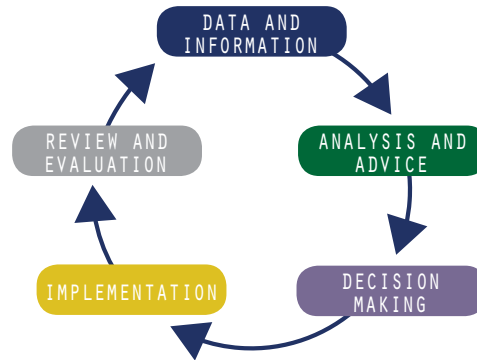
International agreements that have been signed by all countries include the UN Convention on the Law of the Sea (excluding the USA and Venezuela), Agenda 21 and the Convention on Biodiversity (excluding the USA). These agreements already allow for regional cooperation on ocean governance and there are at least 30 regional and sub-regional organisations that provide some level of governance though mainly focused on single sectors such as fisheries, pollution, biodiversity and tourism. In addition to these 'higher level' organisations there are a large number of local and national level groups and organisations, such as fisherfolk cooperatives, conservation NGOs and fisheries departments, that have a role to play in marine governance.

Given the large number of organisations already dealing with governance issues, it would be redundant to create a large region-wide organization to handle all aspects of ocean governance within the WCR. Rather it is better to create a system that enables the existing organisations to communicate and feed into the decision-making process at the appropriate level. This is one of the main aims of the Caribbean Large Marine Ecosystem (CLME) Project which covers the WCR.

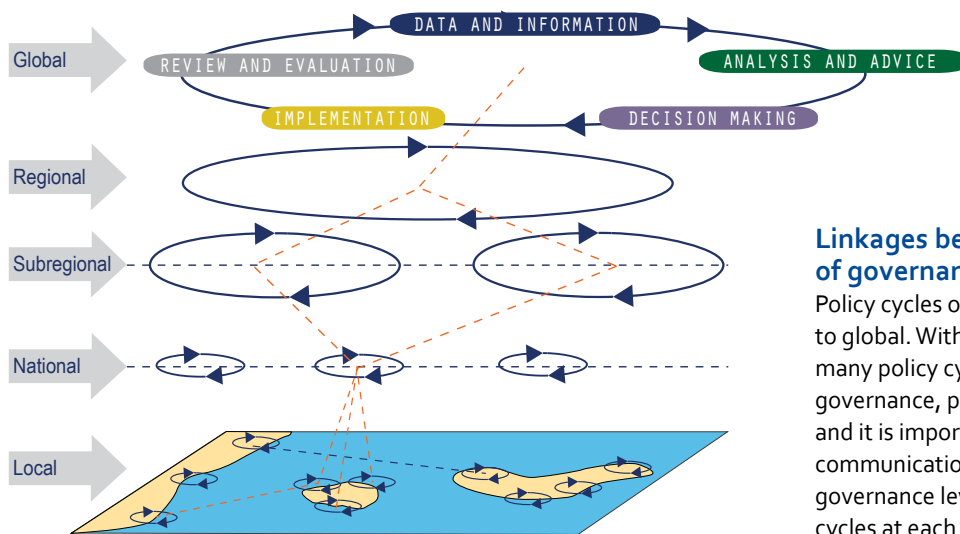


## THE LARGE MARINE ECOSYSTEM (LME) GOVERNANCE FRAMEWORK

A framework has been developed to help understand and improve the governance of large marine ecosystems and this framework is now being used for the CLME. It consists of two fundamental parts of the governance system: a policy cycle and a multi-scale multi-level component (Fanning et al. 2007). The policy cycle attempts to encapsulate the generic decision-making process at any level (local, national, etc.).



Generic policy cycle.



Schematic of linkages between and within levels of governance. Horizontal blue: linkages across within a level, vertical red linkages between the different levels of governance.

### Linkages between and within levels of governance

Policy cycles occur at several levels from local to global. Within each level there may be many policy cycles. For an efficient system of governance, policy cycles need to be complete and it is important that there is two-way communication not only among the different governance levels but also across the policy cycles at each level. This reciprocal communication sharing allows for data and information exchange to inform improvements in governance using ideas from all levels.

### Policy cycle with caribbean large marine ecosystem stakeholders for the reef fisheries and biodiversity pilot project

#### DATA AND INFORMATION

NGO's (Coral Cay Conservation, Coralina, TNC, WWF, WRI, Reef Check, AGGRA, CARICOMP, CZMUs, USG, Center for Climate Change), Universities & Research institutions (UWI, CERMES, ORE MU, INVEMAR, Center for Marine Sciences, CEHI), Fishers/Fishers org., Government Departments (e.g. environment, fisheries), CFMC, Databases (e.g. IABIN, SERVERE, GCRM), CCA, IFREMER, CTO, CRFM, MBRS, ICRAN, MAR, ICRAN, GCFI, Diving associations, UNEP-CAR/RCU, OSPESCA, Local MPA sites (SMMA, Buccoo Reef Trust, Sandy Island, TCMP).

#### ANALYSIS AND ADVICE

Buccoo Reef Trust, Fishers/Fishers Org. TCMP, SMMA Government departments, IMA, CZMU, CRFM, WECAFC, UWI & Academic Institutions, CANARI, Association of Caribbean Marine Laboratories, TNC.

#### DECISION MAKING

Government, CARICOM, ACS, OECS, CARIFORUM, CITES, Private sector (seafood industry), Fishers organizations, FAO, UNEP, CCAD.

#### IMPLEMENTATION

CBO's, NGO's, Fishers co-operatives, Local governance, TCMP, SMMA, Buccoo Reef trust, Government organizations, private sector (hotels, seafood industry, diving), Enforcement & legal entities, Donors facilitating implementation.

#### REVIEW AND EVALUATION

(Buccoo Reef Trust), Fishers/Fishers Org. TCMP, SMMA, Government departments, IMA, CZMU, CRFM, WECAFC, UWI & Academic Institutions, CANARI, Association of Caribbean Marine Laboratories, TNC.

### Coral reef fisheries and biodiversity in the CLME

Two components of the CLME Strategic Action Programme (SAP) that are important for reef managers include addressing the issues of habitat degradation and community modification, unsustainable exploitation of resources and pollution. The focus is on a participatory approach to management involving local people in the management of their own resources. The number of organisations that can be involved in multi-level governance and contribute to each stage of the policy cycle is highlighted above. Fostering improved communication and cooperation among these organisations will help the management of coral reef resources throughout the WCR.

#### FURTHER INFORMATION

The CLME governance system is reviewed and explained in greater details in (Mahon et al. 2011; Fanning et al. 2013) For a complete review of the LME framework see (Fanning et al. 2007) Full details of the CLME project available at: <http://www.clmeproject.org/>



**Robin Mahon**  
CERMES, University of the West Indies



the degradation  
of reefs over  
my lifetime  
has been  
phenomenal  
and extremely  
obvious ...

*Coral reefs are important for people in the Caribbean for so many reasons ranging from production of food, fish and other things we eat off of reefs, for production of sand to go on beaches, for protection of beaches, for people to enjoy, for tourists to visit and pay money so that tourism operators can earn a living as well. The list goes on but those are the main ones.*

*Well, you can see from colour of my hair that I've been around for a while and yes, I've seen huge changes in coral reefs from when I was young and growing up in Barbados and Jamaica and going to the sea on weekends from as early as I can remember. And the degradation of reefs over my lifetime has been phenomenal and extremely obvious to anybody who puts their head under the water. So the depletion of fish and reduction of coral cover and just the way the reef looks, from a healthy reef to one that's covered with algae, just hits you like a ton of bricks.*

## RESEARCH

As part of the social science (team) and governance team we are investigating what are the major factors influencing the governance of reef systems and what kinds of approaches or governance reforms are needed to address the problems.

1  
Governance framework to  
support reef management



2  
An introduction to  
social network analysis for  
coral reef governance



3  
Information brokers  
in reef governance



4  
Assessing the proximate  
and ultimate drivers  
of reef health



5  
Identifying and addressing  
governance constraints  
to reef management



6  
Exploring community  
futures for reef governance



# Governance framework to support reef management

*Policy cycle with feedback  
from meeting participants.*

*'Everything has  
to do with the  
governance,  
I think Governance  
needs to involve  
all actors'*

Meeting participant,  
Honduras 2011

*Workshop participants  
in Barbados discuss the  
policy cycle for coral reef  
management.*

## THE EVIDENCE

Research in the FORCE project has pursued evaluation of governance arrangements at local to national levels within the context of the broader, multilevel ROGF. It seeks to broaden the understanding of good governance for reefs at these important local and national levels and to provide recommendations on how to strengthen these arrangements to better support management efforts.

### Basic features of the ROGF

The ROGF reflects two key governance ideas: the need for a complete policy cycle and nested, multi-level arrangements. In a nutshell, the theory states that if you have a complete policy cycle then good governance is more likely. Good governance is considered a prerequisite for management efficacy and needs to take account of multi-level arrangements. The multilevel schematic reflects the lateral and vertical linkages that must be in place within and between policy cycles at different levels which are needed for effective governance (Policy cycle p.119).

There are over 25 organizations involved in regional ocean governance leading to a set of nested arrangements addressing the key issues of over-exploitation, pollution and habitat degradation. The reef governance arrangements that are the focus of FORCE research are nested in the ROGF.

## THE ISSUE



*Many countries and people in the Wider Caribbean Region (WCR) depend on reefs for livelihoods, food security, culture and recreation amongst many possible benefits. The health of Caribbean reefs has deteriorated because management arrangements have failed to cope with pressures like overfishing and pollution, and now climate change is adding further pressure to the reefs.*

*Reef management – arrangements in place to achieve sustainable use of ecosystem goods and services from coral reefs – is often pursued without consideration of the broader governance (decision-making) structures within which it takes place. Good governance structures and processes, such as transparency, fairness, accountability and inclusion of stakeholders in decision-making are important to ensure that management is context-specific and more likely to be supported by resource users.*

*A Regional Ocean Governance Framework (ROGF) aimed at promoting good governance within the WCR was developed in the Caribbean Large Marine Ecosystem (CLME) Project. The ROGF is mainly about regional level arrangements; however, these can only be effective if supported by good governance at local to national levels.*

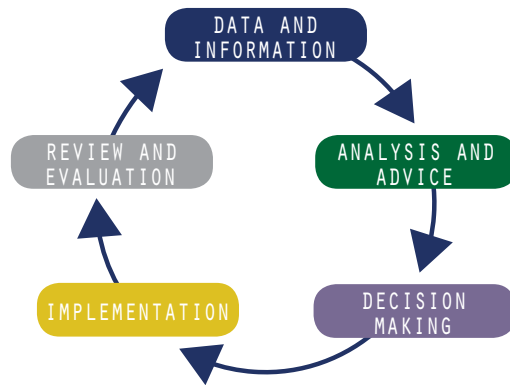


## THE APPROACH

The policy cycle is a generic governance process that may occur at any level (local to global) and must be complete in order to be effective. A policy cycle review was designed to explore the groups and organisations involved in reef management and governance. This process involved:

- Identifying the government, non-government and private sector stakeholder groups involved in formal and informal governance structures that exist and govern natural resource use;
- Identifying groups involved in the governance policy cycle;
- Identifying strengths and weaknesses in the cycle.

The policy cycle exercise was undertaken at national level meetings in four countries – Barbados, St Kitts and Nevis, Belize and Honduras.



## 5 STAGES OF THE POLICY CYCLE

To achieve effective governance, a complete policy process is advisable. This includes the ability to take up data and information, generate advice, make decisions, implement decisions, and review all aspects of the process. Key strengths and weaknesses in the policy cycle were identified by participants at meetings in the four countries studied as part of the FORCE project.

*'For smooth governance of the people you've got to earn the people's trust'*

Meeting participant,  
Barbados 2011

### DATA AND INFORMATION

#### Honduras

Improved data analysis, greater communication, and information-sharing is needed to support policy. Organisations are seen to be competing rather than working towards common goals due to unclear objectives despite complementary roles and responsibilities.

#### Barbados

Stakeholder involvement is present in the 'data and information stage', but the information is not currently being used by decision makers.

#### St. Kitts & Nevis

Transparency and collaboration between departments is weak. It is difficult and time-consuming to share data between agencies due to lack of standardised system for data collection and management

### ANALYSIS AND ADVICE

#### Honduras

It was perceived that recommendations about reef management proposed by stakeholder groups are not considered by central government. Much data has been collected but few are able to analyse the data and form recommendations.

### DECISION MAKING

#### Barbados

Participants noted that the decision making authority is highly centralised, mainly residing in the Prime Minister's office. Data are not being used in decisions made.

### IMPLEMENTATION

#### St Kitts & Nevis

Country has received funding, though desired environmental outcomes have not always been achieved. Projects are duplicated and/or implemented haphazardly.

#### Belize

Resources in the implementation phase were perceived to be lacking; decisions and management plans are created, but not enough resources to implement them.

#### Honduras

Participants felt improvements to the policy cycle could include greater resources for implementation (particularly for enforcement).

### REVIEW AND EVALUATION

#### Belize

Participants identified a lack of review and evaluation, and a lack of feedback in the system. Not enough people focused on adaptive management, more groups needed in this area.

#### Honduras

Although many stakeholders generate information relating to reef management, participants felt there is little review and evaluation of this information, and data is not communicated effectively to decision-makers.

## MANAGEMENT IMPLICATIONS

Identifying actors (individuals or organisations) involved in a policy cycle, along with its strengths and weaknesses, as well as opportunities for improvement, can build awareness of the many organisations that can potentially be better involved in reef governance. Fostering improved communication, coordination and cooperation among these organisations through application of good governance structures and processes at different levels should improve the management of coral reef ecosystems throughout the WCR.

## FURTHER INFORMATION

In depth information on the Caribbean Large Marine Ecosystem Governance Framework is available via:

[http://cermes.cavehill.uwi.edu/LME\\_Gov.html](http://cermes.cavehill.uwi.edu/LME_Gov.html)

## An introduction to social network analysis for coral reef governance

*Fishers and tourism operators in Barbados.*

*Social network analysis (SNA) is the study of actors (individuals or organisations) and the relationships that connect these actors.*

### THE APPROACH

In SNA, data are collected on relationships between individuals and/or organisations. Some examples of these relationships include: family ties, exchange of resources such as money or information, assistance given or received, membership of similar groups and shared attitudes or beliefs.

Example: To study relationships between fishers in a given community, a researcher might ask, "Which fishers in this community do you share information with about fishing?" or "Which of the fishers in this community would you consider a friend?" These questions would elicit two different networks from the same group of fishers; each potentially having a different use for managers. A network based on information sharing might be useful for managers when trying to disseminate information to fishers or gain understanding of how local ecological knowledge is transferred. A friendship network may be more important when trying to build support for new management measures.

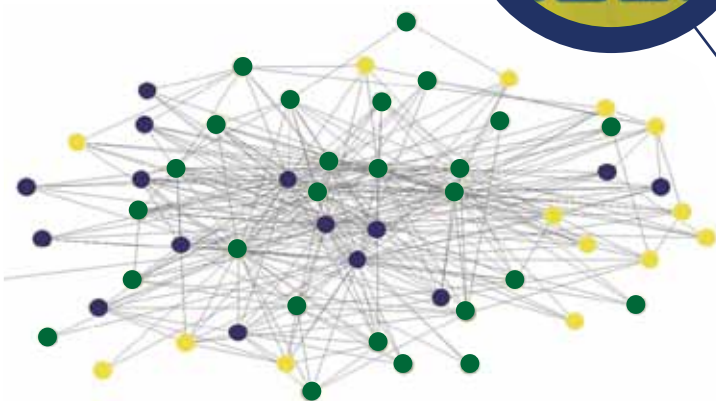


*A wide range of actors both public and private are involved in the use, management and governance of coral reefs. These actors range from those who depend on the reefs for their livelihoods, to the local organisations who manage the reefs, to government agencies involved in policy and legislation development.*

*Management benefits from an understanding of the interactions between people and coral reefs. Similarly, relationships between the actors involved can contribute to the failure or success of governance and management outcomes. Social network analysis (SNA) is one tool that is being used to better understand these relationships.*

### ACTORS - NODES

- Government agencies
- Organisations
- Resource user groups and associations



*SNA can be used to create sociometric maps. This diagram presents a coral reef information sharing network for Belize. The nodes (dots) in this network include national level actors and local actors from three communities. Ties (lines) represent information sharing to or from another actor.*



### THE TIES

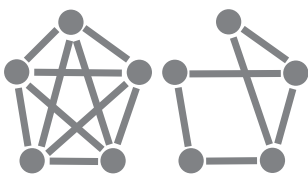


**DENSITY**

**Total number of ties as a proportion of total possible ties.**

**Positive:** High densities can lead to greater communication, knowledge development, exchange of ideas and resources, and build trust.

**Negative:** Potential for high densities to reduce input of new information and knowledge, resulting in reduced adaptive capacity, resilience, and innovation.

**PATHLENGTH**

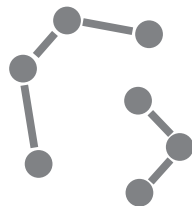
**Distance between any two nodes.**

**Long path length:**

Information and resources typically not available or accessible. Flows between nodes less efficient.

**Short path length:**

Information and resources more accessible. Shortened feedback loops can help maintain and build resilience

**CENTRALITY**

**Identifies nodes that are more 'central' based on the number of ties they hold.**

**Positive:** Actors with high centrality can coordinate and help spread diverse knowledge and resources

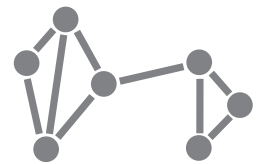
**Negative:** An actor may be unaware of their position, unwilling, or unable to facilitate exchange, functionally blocking the connections between other actors

**SUBGROUPS**

**Subsets of nodes that have a high density within the subset.**

**Positive:** Subgroups can be important for holding varying information and ideas, facilitating work and progress towards goals, and can increase adaptability. Greater ability to build and maintain trust and cohesion within groups.

**Negative:** Potential of forming an 'us vs. them' mentality.

**MANAGEMENT IMPLICATIONS**

**There are several ways SNA could be applied to coral reef management:**

- With knowledge of an information-sharing network, managers can target a few select individuals in the best positions to help them spread new information more effectively. This might be useful when new rules or regulations have been put in place but previous attempts at advertising these changes have not been effective.
- Leaders and influential individuals may not be directly obvious to a manager, yet may be critical in building support for a new initiative. SNA can identify these individuals and allow managers to better understand the roles of these individuals in the network.
- People or groups that are marginalised or isolated can be identified, allowing managers to build outreach and engagement activities to better include these actors.
- Individuals or organisations can be in positions critical to the flow of information. However, they might not be aware of the importance of the position they hold, potentially blocking or reducing information sharing in the network. Their removal from the network (like an individual leaving a job or moving to another community) could remove the only pathway for information to be shared between different groups. Identification of these critical individuals or organisations can allow managers to support them in their role, while promoting additional relationships to reduce reliance on a single individual or organisation.
- SNA can identify decision-makers' sources of information, e.g. are decision makers connected to information representing different types of stakeholder groups? Local ecological knowledge? Research institutions? Evidence-based decision-making requires information from a range of sources; SNA can highlight gaps or bias in information received by decision-makers.



*Local marine map from Honduras.*

**Networks in Caribbean reef governance**

Reef-related information sharing networks show different patterns of interactions. In St. Kitts for example, information sharing was found to be highly centralised around a single government department responsible for marine resources. In the Bay Islands of Honduras, fishing and tourism resource users were primarily exchanging information with local NGOs in charge of managing MPAs and had virtually no contact with government agencies. Belize, by comparison, had high levels of information sharing between resource users, local NGOs, and government agencies.

*Fisheries enforcement officer badge Belize.*

# Information brokers in reef governance

Local dive operator,  
Roatan Honduras.

*A broker is an actor (organisation or individual) that connects two otherwise unconnected actors. Brokers are sometimes known as bridging organisations.*

## THE EVIDENCE

Interviews with reef resource users, NGOs, and government agencies were conducted in four countries (Barbados, St Kitts and Nevis, Belize and Honduras) to map information sharing networks and identify reef-related information brokers. Resource users' perceptions of information sharing and opportunities to participate in decisions made about reefs were also assessed.

Social network analysis found that resource users were typically not well integrated into the information sharing networks. Local reef managers, environmental NGOs, or national fisheries agencies were most frequently found in positions to broker reef related information between resource users and other actors in the networks. However, these organisations and agencies were not always acting as effective brokers.

Evidence suggests that NGOs are more effective at sharing information with resource users. In communities where resource users were more likely to get information about reefs from an NGO, in particular NGOs that act as local reef managers, the users were more likely to feel like they have an opportunity to participate in decisions made about the reefs. Though government agencies were identified as brokers, they were less effective at reaching individual resource users.

Roatan Marine Park,  
Honduras.

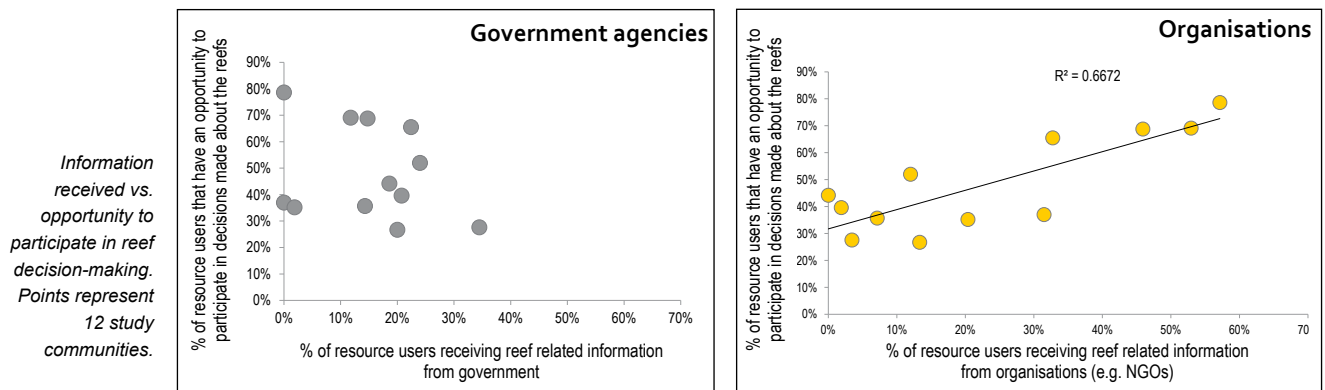
## THE ISSUE



*Coral reefs are part of complex social-ecological systems and successful management of these systems requires the integration of people that use and depend on the reefs for their livelihoods. Including resource users in decisions made about reefs, especially those decisions that may impact their activities with reefs, can give rise to many benefits such as increased compliance with regulations and reduced management costs. However, many resource users are often not involved in or made aware of the decision-making process.*

*Brokers connecting resource users to decision-making bodies are thought to be critical in adaptive management. In coral reef governance, brokers are often local reef managers, though could be resource user associations such as a fisherfolk cooperative, individuals, fisheries officers, environmental NGOs, or even businesses. Their position allows them to hold information from a range of sources, respond early to threats and changes, and see new opportunities. Understanding brokerage relationships and their effect on governance outcomes (e.g. stakeholder participation) is a crucial step in navigating the complex socio-ecological systems of coral reefs and implementing successful management.*





The types of actors in significant roles brokering information to and from resource users in each study site corresponded with presence and management type of marine protected areas (MPAs). Significant brokers of reef-related information to/from resource users were identified for each of the study sites. The type of actor in these positions corresponded with the type of management present at the site.



### Brokers can encourage participation

Over 78% of resource users from West End in the Bay Islands, Honduras stated that they had the opportunity to participate in decisions made about the reef. Roatan Marine Park (RMP), a community based NGO that co-manages the marine park, had a strong presence in West End. Signs from the marine park were frequent throughout the community informing users and visitors about the area. The dive shops in the community visibly supported the marine park and their endeavours. When asked who they received information from about the reefs, over 55% of resource users responded with the Roatan Marine Park. In addition to being an effective source of information for local resource users, the marine park was well linked to government agencies and other NGOs in the country.

## MANAGEMENT IMPLICATIONS

The research highlighted here demonstrates the importance of organisations in brokering information to resource users. Information sharing, depending on the source(s) (e.g. NGO, government agencies) and the method(s) of interaction (e.g. community meetings, newsletters), is an important part of resource users feeling like they have an opportunity to participate in decision-making. Benefits from participation can include increased cooperation, higher perceptions of fairness of decision-making, increased compliance with regulations and reduced costs of management. It is important to recognise and support organisations and agencies that facilitate information exchange with resource users.

**Many factors can affect the efficacy of a broker, a few points to consider are:**

- The quality of information shared
- Method(s) of sharing; face-to-face interactions are more likely to lead to positive outcomes
- History of relationships between the broker and other actors
- Personal relationships (e.g. familial, friendship) of individuals within the brokering organisation and individuals in other groups
- Continuity and consistency of interactions



*Brokers help to bridge gaps that may exist due to barriers such as language, geography, or social strata.*

## Assessing the proximate and ultimate drivers of reef health

Vibrant reef in Curaçao.

### THE EVIDENCE

Interviews were conducted with a range of reef stakeholders in four countries (Barbados, St Kitts and Nevis, Honduras and Belize) to assess their perceptions of the drivers of reef health. These stakeholders included community households and 'key informants' such as local level community reef managers and national reef managers and policy makers.

A wide range of proximate and ultimate drivers to reef health were identified by interviewees. In total 39 proximate and 79 ultimate drivers were mentioned. The community interviewees mentioned 33 proximate and 48 ultimate drivers, compared with the key informants who collectively mentioned 37 proximate and 76 ultimate drivers.

At the community level, people were most concerned with proximate drivers relating to pollution, rubbish and physical damage. Ultimate drivers relating to unsustainable tourism, snorkelling and diving, and coastal development were also commonly mentioned. In contrast, key informants were most concerned with ultimate drivers relating to non-compliance, enforcement, and resources and capacity, leading to ineffective reef management. Proximate issues relating to unsustainable fishing, pollution and physical damage were also commonly mentioned by key informants.

Snorkelling in Honduras.



*Caribbean reef health has declined rapidly in recent decades, with predicted impacts from climate change expected to put more stress on reefs over this century. At the same time, the demand for ecosystem services provided by reefs is increasing. Reef management is likely to be easier where people have a good understanding of the causes and consequences of changes in reef health and how they are affected by them.*

*It can be easier to manage a threat when it is well understood. Recognising both the proximate and ultimate drivers of change in Caribbean reef ecosystems will aid understanding. Research has largely focused on understanding the proximate causes of impacts to reefs, such as the lack of fish, nutrient levels, and so on. Studies of the ultimate drivers attempt to identify the ultimate – often social – reasons that these problems exist. Because these tend to involve people, this is where management can have an impact.*

**Proximate drivers act directly on the reef, e.g. coral bleaching, pollution, and hurricane damage**



Pollution



Invasive species



Coral bleaching



## MANAGEMENT IMPLICATIONS

The research highlighted here demonstrates the complexity of impacts affecting coral reefs, and the importance of increasing our understanding of ultimate and proximate drivers of reef health. Reef management may be improved by taking two key issues into consideration:

- Identifying the ultimate drivers that act through proximate drivers can help address the underlying causes of reef degradation.  
**Example** Sediment is one of the proximate drivers. One of the ultimate drivers might be poor coastal development practices that increase sediment on reefs. Hence improving coastal development regulations will help reduce sediment. Focusing only on the sediment (proximate driver) as the problem, e.g. trying to divert sediment flows away from the reef, might be useful but would not address the ultimate driver of increased sediment. Other ultimate drivers in this case might include lack of regulation, lack of political will to regulate and economic pressures to allow development.
- Building a common understanding of drivers between the people that use the reefs and those that are responsible for managing them. If managers' and resource users' perceptions of the drivers of reef health are very different, it may lead to a lack of support for management measures as resource users may not perceive restrictions to be necessary. Identification of differences in perceptions may indicate important areas for potential awareness-raising and education.  
**Example** If managers perceive fishing pressure to be a major driver of decline in reef health, but fishers attribute the decline to other causes such as pollution, attempts by the managers to regulate fishing may be met with resistance by the fishers.



Ultimate drivers may be physically separated from the reef, e.g. overfishing, poverty, climate change, and poor governance.

## Identifying and addressing governance constraints to reef management

*Marine reserve patrol boat in Barbados.*

### THE EVIDENCE

To explore perceptions of the current constraints to reef management, 117 'key informants', including reef managers and policy-makers at local and national levels, were interviewed during the FORCE project. Interviews were conducted in four countries (Barbados, St Kitts and Nevis, Honduras, and Belize) chosen to represent a gradient of governance structures, social and economic conditions, and levels of marine resource dependency in the Caribbean.

Interviewees identified a wide range of constraints to reef governance that were categorised under five themes that describe different aspects of the factors needed for good governance: influencing factors, system governability, governance architecture, governance process, and management.

Constraints in the 'Management' theme were most commonly mentioned. Over 80% of respondents reported challenges related to achieving effectiveness in enforcement, resources, capacity, and compliance.

*The structures and processes that support decision making about the management of coral reefs can be described as reef governance. Good governance is considered important for effective management of coral reefs and other natural resources.*

*Understanding the existing governance constraints can help managers identify the most appropriate management tool to plan for current and future changes.*

*Constraints could include a weak structure where organisations do not communicate with each other and are unaware of institutional arrangements related to reef management ('Governance architecture'). The lack of a governance process to facilitate effective communication and co-ordination (e.g. no clear leadership) is another constraint.*



Constraints relating to governance processes were also commonly mentioned, with four of the most frequently mentioned constraints falling under this category. These included a lack of education and awareness among reef users, which affected how people interact with reef resources; a lack of engagement of reef users and community members; a lack of cooperation and integration among groups and organisations involved in reef management; and a lack of information and research to support effective management of reefs.



Meeting with fishers.

### Governance constraints mentioned by interviewees



#### INFLUENCING FACTORS

Factors external to the reef governance system that influence reef governance. E.g. socio-economic pressures, cultural factors, political will.

#### SYSTEM GOVERNABILITY

Inherent properties of the system to be managed that present challenges. E.g. complexity, scale, dynamics, diversity.

#### GOVERNANCE ARCHITECTURE

The structures or arrangements in place for reef governance. E.g. Institutional arrangements, legislation, regulations and policy.

#### GOVERNANCE PROCESS

Processes, procedures and principles that guide interactions, planning & decision-making. E.g. Leadership, engagement, transparency, connectivity.

#### MANAGEMENT

Implementation of reef governance decisions and factors influencing capacity to manage. E.g. Resources & capacity, enforcement and implementation.

## MANAGEMENT IMPLICATIONS

An understanding of the current governance constraints faced by reef managers can help improve reef management in two ways:

- It can help managers identify particular management tools that may be more successful under the current management constraints.  
**Example** In cases where effective enforcement is perceived to be a constraint, management approaches that aim to increase stakeholder engagement, stewardship and voluntary compliance may be more effective than management tools that rely on enforcement of regulations.
- It can help to identify appropriate and targeted interventions needed to improve governance which in turn can support more effective management of coral reefs.  
**Example** Where a lack of cooperation and integration among reef managers is identified as a problem, efforts can be made to identify mechanisms to improve communication flows among different groups and organisations.

*Governance is the whole of public as well as private interactions taken to solve societal problems and create societal opportunities.*

# Exploring community futures for reef governance

Exploring future scenarios in St. Kitts and Nevis.

*Future scenarios are possible views of the world. They provide a context for decision making. This process can help managers prepare for realistic future challenges.*

## THE EVIDENCE

Conducting scenario workshops with communities that use marine resources differently can highlight many differences in their ability to see and shape their own futures.

Four scenarios are conventionally described, based on two axes designed around critical future uncertainties. This allows managers to see a divergent range of possible worlds. The process is structured to allow people to start 'consciously' thinking about the future. Data are less critical than the process: this should be creative and shared, allowing time for reflection about the future of the resource and dependent communities.

The following pages describe the futures process undertaken by the FORCE project. Examples of data generated by meeting participants in the Bay Islands of Honduras are then presented. The technique specifically aims to encourage discussion of 'extremes'. Narratives are polarized by design, but realistic glimpses of possible future worlds are visible within each.

A focal question was identified. "How can we best address threats to coral reef systems and the coastal communities that depend on them, and support coral reef management/governance in the future?"

Reef tourism.

## THE ISSUE



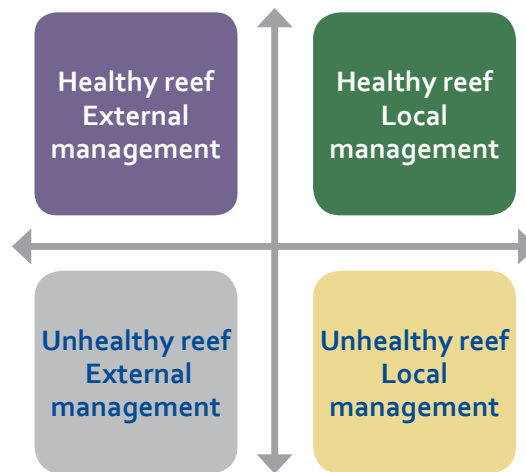
*Coral reefs are part of complex social- ecological systems and sustainable management of these systems requires the integration of people that use and depend on the reefs for their livelihoods now, and their engagement with a future in which reefs remain important. Sustainability requires "development which meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987) and reef managers must try to incorporate such future needs.*

*Structured techniques have been developed to encourage 'futures' thinking. Scenario work is one approach. To operate in an uncertain world, managers need to be able to question their assumptions about the way the world works. Decisions can be better informed, and strategies based on this knowledge and insight will be more likely to succeed. Scenarios describe plausible future worlds, but do not seek to predict the future.*



Critical uncertainties were then defined as:  
a) whether future decision making would be internal (i.e. local management) or external to the community, and b) the health of marine resources (healthy/ unhealthy reef); leading to a scenario matrix.

Community meetings were conducted. Members of each community were invited to discuss each of the four plausible futures in small groups. Workshops were planned for each study site. Ten communities (Barbados 3, Honduras 3, St. Kitts 2 and Belize 2) ultimately participated in the facilitated discussions.



Scenario matrix.



Visions of community futures in the Bay Islands of Honduras.

#### LOCAL MANAGEMENT

Ecosystem dependent businesses flourishing, co-operatives ensure all benefit, positive feedbacks as tourist target species and ecosystems protected.	Cooperation creates high value island brand. Grants set fishers up with new professions, in diversified tourism industry (terrestrial takes pressure from marine). Lots of fish, impressed tourists, more work. Better education; everyone proud of healthy environment.	Culture shift – pride in all aspects of environment. High value reef – brings high value tourism; more jobs, more responsible cruise ships. People with more disposable income. Greater education. Marine park with more power and authority.
No tourism, no fishing, regulation means people can't live. Cays forgotten by government which allows resource depletion.	People live in poverty - islanders and mainlanders. No collaboration between communities. Low value tourism. Wholesale environmental damage – rubbish, pollution, reef damage – no one cares.	No resources, so no tourism. Locals resist government as taxes are taken and nothing is given back. Exodus of mainlanders and islanders – people seek work elsewhere. Increased crime, alcohol, drugs, corruption; decreased education/opportunity.

**Healthy reef  
Local  
management**

**Unhealthy  
reef  
Local  
management**

#### EXTERNAL MANAGEMENT

Government protect more and provide more projects to give people alternatives/ help people support their families. Lots of tourism, big taxes to government. More rules to protect marine species. People obey laws.	National marketing as a tourist destination. High employment. Support for local business, e.g. Microfinance. More alternative jobs and education so less fishing. Government regulate development -carrying capacity assessed. Stricter enforcement; population control. Equity of regulation and enforcement.	Increase in foreign investment, revenue generated for government, land in foreign hands, injustice and lack of equity for local people, increasing crime. Support for improving education and awareness, but jobs for local people limited to service level.
Greater regulation, ecosystem based livelihoods abandoned, government support for new alternatives needed, communities supported by state.	Government abdicates responsibility for islands, no distribution of wealth. Corruption rife. No reef, no divers, no income. Resources exported. No incentives for businesses to stay, unemployment.	Big multinational companies in control, not government. More cruise ships, more damage, no corporate social responsibility. Resource deteriorates Tourism value drops, industry disintegrates.

**Healthy reef  
External  
management**

**Unhealthy  
reef  
External  
management**

## HOW IS IT DONE?

By following a structured process, scenarios aim to capture four very different, but 'plausible', futures, including both good and bad aspects. These seek to maximise the diversity of futures imagined, to allow managers to plan proactively, developing policies that are robust against a wide variety of possible future events.



1) Find a venue. Invite community members who have attended interviews and project meetings.



2) Review project findings. Introduce thinking about the future on the basis of trend that community has previously identified.



3) Introduce structured scenario approach to thinking about the future, and explain the exercise.



4) Allocate a facilitator and a note taker to each group, to help with and record discussions. One person per group writes up main points for the wall.



5) Break into groups, ideally one group to discuss each scenario.



6) Facilitators stick main points onto the wall during the course of discussions, picking out the main themes as they go.



7) Until the full picture emerges.



8) The main themes emerging are discussed, and contributors have an opportunity to see the 'other' three scenarios.



9) Participants review all scenarios and are asked to vote on what aspect (across all worlds) they think most likely to actually happen in their community in the future.



10) Participants also vote on the element that they think would have the biggest impact if it did occur in their community.



11) Main events and weightings are then analysed to identify priorities for management. i.e. avoiding pathways that could lead to the 'greatest impacts'.

## LOCAL MANAGEMENT: CAPACITY TO ACT

**Fishing Community**

Like the idea of this, but have little concept of the actions required to get there, still reliant on 'government' to help.

**Mixed Use**

Detailed vision of actions required to create a more positive environment, community will to achieve this.

**Tourism Community**

As fishing, but appear to perceive that they would have less control in any future as the multi-nationals already have a strong hold.

**Fishing Community**

Little concept of being able to take control without guidance.

**Mixed Use**

Scraping by in a deteriorating environment, knowledge that behaviour change is required to avoid this – community seems to have capacity to take action.

**Tourism Community**

Strong people with broader perspective of possibilities elsewhere - options to leave.

## EXTERNAL MANAGEMENT: WILLINGNESS TO ENGAGE

## MANAGEMENT IMPLICATIONS

Scenarios do not predict the future, but do illuminate drivers of change. Understanding them can help managers working with communities to develop successful conservation actions.

**Example** *If local populations are predicted to expand, proactive sustainable local development (housing) and food security (fishing vs. other protein sources) plans must be updated if coral reefs are to be adequately prioritised.*

The main value in the process is the development of shared views of the future. This can be used to create opportunities for groups with common aims to consider how they want to position themselves in those futures.

**Example** *Indigenous Garifuna people in Hopkins, Belize have developed cultural tourism in community groups to take pressure off declining reef tourism resources.*

## FURTHER INFORMATION

Most major government departments around the world use foresight methods similar to those discussed here. Many resources are available, e.g:

[www.bis.gov.uk/foresight](http://www.bis.gov.uk/foresight), [www.dlr.de/](http://www.dlr.de/), [www.ipcc.ch/](http://www.ipcc.ch/)

The Brundtland Report 'Our Common Future' – UN 1987  
<http://www.un-documents.net/our-common-future.pdf>

# Livelihoods



*Coral reefs not only play a critical role in ensuring the health of coastal and marine ecosystems, they also underpin many aspects of the lives of people who live in the Caribbean. Many of the livelihood activities of people in the Caribbean depend directly or indirectly on the services provided by coral reefs in the form of: fish for food and sale (provisioning services); the maintenance of overall ocean health and productivity (supporting services); coastal protection (regulatory service); and the provision of recreational and cultural activities (cultural services).*

*People's dependency on the reef has often led to an approach to managing coral reefs that has focused on controlling human activities that are seen as detrimental to reef health. However, undertaken in isolation, efforts to control or eliminate those human activities have often proved ineffective or damaging to people's livelihoods. This is frequently because of failure to fully understand how coral reef use (including unsustainable and destructive uses) interacts with the other activities that coral reef users undertake, the complexities and dynamics of the setting in which they live and the linkages between the different elements that make up the 'livelihoods' of coral reef users. The Caribbean reef livelihoods framework detailed here can be used to better understand the complexities of the interactions between people and reefs, and how livelihoods are affected as a result of these interactions.*



Fisheries and tourism provide important livelihood opportunities in the Caribbean.

## UNDERSTANDING LIVELIHOODS



Fruit stall in Jamaica.

To begin to understand the complexities of the interactions between reefs and reef-dependent people it is useful to apply the Sustainable Livelihoods Approach (SLA) to this interaction. The result has been the development of a Caribbean reef livelihood framework. This can be used to understand the interactions between people and reefs, to develop appropriate responses to reef livelihood dependency and to ensure sustainable reef-use. This is particularly important in the face of climate change which threatens to undermine many of the livelihood opportunities now available to coastal people.

The term 'livelihoods' has come to be increasingly associated with efforts to improve the management of coral reefs. In particular, coral reef management initiatives with 'alternative livelihoods' interventions are becoming more common. These generally aim to improve the effectiveness of coral reef management measures by providing alternative forms of income-generation to those



Local restaurant on the beach.

people who are negatively impacted by new management measures that may have deprived them of access to important resources on which they depend.

Detailed evaluations of alternative livelihoods initiatives have been rarely carried out, but there is a growing consensus that their effectiveness has been mixed (Haggblade et al 2002; IMM et al. 2005; GEF 2006). This failure to match expectations can be attributed to a lack of understanding of the complexity of livelihoods. Coral reef managers would benefit from a good grasp of these complexities if they are to incorporate human dimensions into their management plans.

Understanding of livelihoods, and the factors that are likely to make livelihoods sustainable in the face of change, need to take account of a broad range of factors and influences that may play a role at multiple levels. These levels range from the individual, to their immediate household, to the surrounding community, right up to policy and decision-making at the national and international levels, as well as at the level of society as a whole.

### Defining 'Livelihoods'

*"A livelihood comprises the assets (natural, physical, human, financial and social capital), the activities, and the access to these (mediated by institutions and social relations) that together determine the living gained by the individual or household".*

Ellis F., 2000. Rural livelihoods and Diversity in Developing Countries. Oxford University Press.

*"A livelihood comprises the capabilities, assets (including both material and social resources) and activities required for a means of living. A livelihood is sustainable when it can cope with and recover from stresses and shocks and maintain or enhance its capabilities and assets both now and in the future, while not undermining the natural resource base".*

Carney D. (ed) 1998. Sustainable Rural Livelihoods: What Contribution Can We Make? Papers presented at the DFID Natural Resources Advisors' Conference, July 1998. DFID.



## CARIBBEAN LIVELIHOODS FRAMEWORK

First of all, livelihoods are not just about how people earn a living or produce food, but need to be understood holistically. Some of these key elements, and the relationships among them, are shown in the Caribbean Livelihoods Framework. In this framework, a key starting point for understanding livelihoods is placing **PEOPLE** at the centre of the analysis. Understanding people's diversity and their different characteristics as individuals (**WHO THEY ARE**) is key in attempting to understand their livelihoods. The livelihoods of men will usually be significantly different from the livelihoods of women; older people may have different relationships to different elements in the framework compared to younger people. Ethnicity, personal and family history, linguistic and cultural background, and relative ability or disability may all have a critical influence on how people are able to create a livelihood.

This focus on people is critical because different people have different levels of access to the assets or capital that they make use of to create a livelihood. Gender, age, ethnic group, socio-economic standing or personal history will all affect how people are able to access and use different types of natural, social, physical, financial and human assets (**WHAT THEY HAVE**). For example, women may have different levels of access to education compared to men, which will affect their human assets, while older people may have very different social networks compared to younger people, affecting their social assets.

Livelihoods cannot only be understood by looking at the level of individuals or households, but need to include an understanding of the formal and informal institutions around them, policies that may affect them, and the processes going on in wider society that influence how they are able to pursue a particular livelihood. The Caribbean Livelihoods Framework focuses on three key areas of these policies, institutions and processes. These will often operate at different levels – the community that reef user households live in; the wider area or region where they are located; and nationally. Public and private service providers will often play a key role in affecting how people are able to access critical assets, including food to buy, equipment they need to produce food, services like transport and power, access to finance and credit, as well as to healthcare and education. In turn, the way these service providers function will be determined by policies, legislation and resources usually decided upon at higher levels by controllers or rule-makers. These include elected representatives whose task is to decide



on legislation, policy-makers, civil servants, the judiciary, and all those who set the rules that determine what people are able to do to create a livelihood for themselves. More intangible influences from factors that may not be linked to specific organisations but which permeate society, such as power, communication, markets, norms and values, and culture or tradition, will often be as important as other more structured institutions.

*The Caribbean Reef Livelihoods Framework aims to provide a lens through which the livelihoods of people living in the Caribbean and depending on coral reef resources, whether directly or indirectly, can be interpreted.*



### The influence of people's background on opportunities in the tourism industry

*In many communities studied by the FORCE project there were strong perceptions that access to opportunities in tourism tended to be dominated by 'outsiders' – either foreigners or people from outside the local community – largely because they have better access to the capital required for investment in tourism facilities. Particularly where tourism has led to changes in access to beach areas and the use of the coast, this can affect local people's attitudes to tourism and to efforts to protect the reef areas which attract tourists. Age also plays an important role in people's perceptions of the opportunities that they can take advantage of in tourism. Older fishers often seem to have greater difficulty in adapting to changes in fishing access while younger people may find it easier to diversify their activities to take advantage of new opportunities in fishing.*



*Cleaning fish in Barbados.*



*Boats and fishing are an essential part of peoples livelihoods.*

Reef managers need to be able to understand the relationships between people and their surrounding environment if they are to understand how people make decisions about their livelihoods. The way these linkages and relationships between people, service-providers, and rule-makers work are critical in establishing what sort of livelihood options are open to people.

### Communication, transparency and fishers' perceptions of fisheries regulations

*A recurring theme in discussions held with fishers was the lack of communication regarding new fisheries regulations prior to their introduction. Fishers in Barbados, Honduras and Belize all described how they often found themselves prevented from fishing, either in new protected areas or because of new licensing laws, without ever being informed or having a chance to comment on the new laws. Failure to take account of damage to fishers' livelihoods or to accommodate long-standing fishing traditions when formulating new regulations was a particularly sensitive issue. As a result, fishers often saw these regulations as an unfair imposition, even though they often agreed in principle with the need for controls on fishing activity. Others commented on how implementation of regulations was often uneven or influenced by family connections and preferences. As one fisher put it: "...if [they] don't like you they put you in jail but if they like you they leave you and let you go. That's the way it works..."*



*Sea urchin harvest in the past.*

For example, rules may have been established about reef access and use at the national, policy-making level. However, if they are not effectively communicated to people who make use of those resources, or if they have been determined with limited consultation of the people directly involved, they may be perceived negatively, or ignored. Similarly, even if rule-makers have communicated with the service providers (such as Fisheries Officers or Park Managers) who are responsible for enforcing them, if they have not also provided the resources necessary to carry out enforcement, the rules may never be put into effect. In turn, the effectiveness of enforcement will often be determined by the relationships between enforcers (service providers) and reef users. If there is limited communication and consultation between the two, and if local institutions and leaders are not involved in the process of enforcement, regulations may be ignored or opposed by resource users.

Thinking about the quality of these relationships is therefore important. These 'qualities' include, for example, the extent to which there is effective communication in these relationships (e.g. Do rule-makers and service providers listen to what resource users are saying? Is there effective communication between the people who make rules and regulations and the service providers who have to enforce them?) Transparency and accountability in these relationships is also an important quality. This might mean that the people who make rules and laws be held accountable for their decisions and the process of decision-making is made clear to everyone. Service providers should also be held accountable for the quality of their services, both by people on the ground and rule-makers. Often working to improve these relationships, such as by increasing accountability and transparency or creating opportunities for participation and communication from both sides in these relationships, can be more important for people's livelihoods than simply providing them with new sets of assets or training them in a new type of activity.

The ways in which people interact with service providers and rule-makers are also affected by wider processes in society: factors like politics, power relations, dominant values, markets forces, and the ways in which people's rights are recognised and upheld. Clearly, many of these factors are difficult to change in the short term, but the ways in which they influence people and institutions need to be understood and taken into account.

As shown in the framework, all these complex interacting factors operate within a broader context of external challenges. These are factors over which it may be very difficult to exert any direct influence. These external elements include shocks like hurricanes or earthquakes, cyclical changes like seasonality, or very long-term processes such as rising populations or climate change. These external factors may be very difficult to avoid, but the extent to which people can respond and be resilient in the face of these factors will depend very much on how effectively the relationships at the centre of the framework function: if decision-makers and service providers are supportive of people in their attempts to create a viable livelihood and the linkages between them are strong, people's resilience and capacity to adapt to external changes is likely to be better.

For the people at the centre of this framework, their choices regarding their livelihoods, and the way they respond to different changes in the many elements that make up their livelihoods,

### Local politics, power relations and social networks influencing enforcement of fisheries regulations – for better and for worse

*On small Islands in the Caribbean, the small population size and close relationships between resource users and resource managers often influence the regulation of the fishery. Enforcement of regulations is perceived to be difficult as perpetrators of violations may often be friends or family of enforcement officers. Family connections, private interests and political factors affect how the fishery is managed and the access of individuals or groups to resources (Korda et al. 2008). These influences can work both ways: in Jamaica, local rangers were able to encourage family and friends to voluntarily comply with regulations by appointing community leaders as enforcement officers to create 'community policing'. These individuals have been able to prevail upon others not to embarrass them by violating the rules (Espeut 2002).*

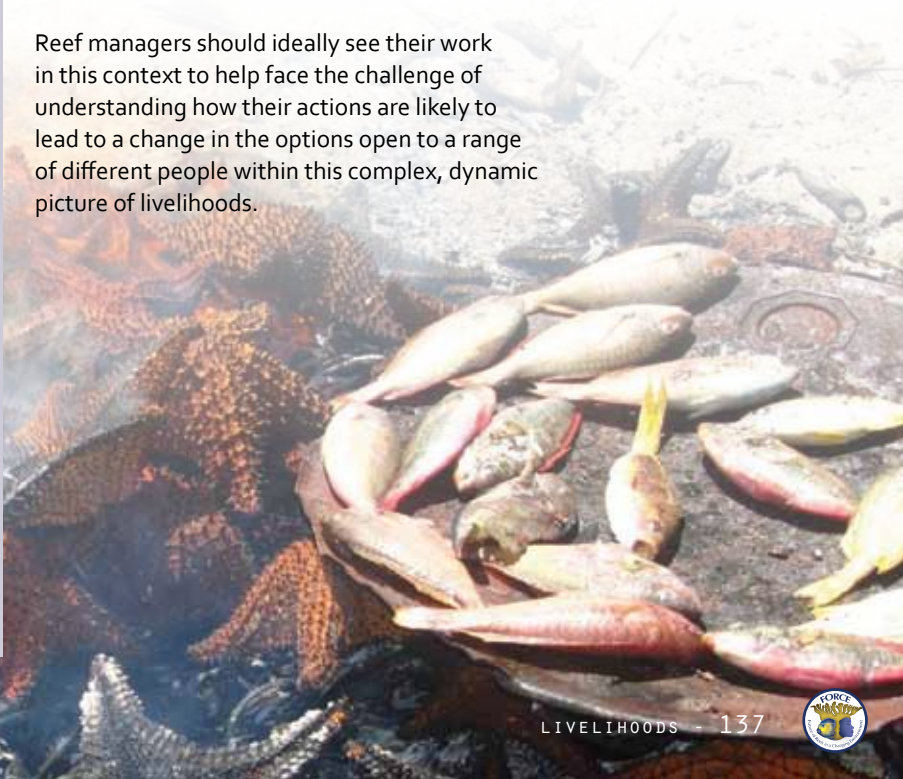
### Dealing with the impacts of economic trends

*Tourism, as an industry, is strongly affected by world-wide economic trends and market forces over which those employed in the industry have little direct influence. The economic downturn experienced in the US and Europe during 2008-2009 directly impacted on tourist arrivals in the Caribbean and a decline in employment opportunities affected people who had taken up jobs in hotels and services for tourism. Respondents in St. Kitts and Nevis noted that "...experience has taught us that this industry (tourism) is very fragile and you never know" and that "...tourism is a fickle industry...". It was seen as important to have other livelihood options available in order to deal with the periodic downturns that the industry experienced.*



are determined by how all of this fits together. Reef managers need to recognise that often their interventions represent just one part of this more complex picture - their focus may be on improving the sustainability of one particular set of natural resources that people regard as a livelihood asset, e.g. fisheries. The way people respond is likely to take into account a very wide range of different influences. These will determine people's hopes and aspirations for the future, their perceptions of what constitutes an opportunity or a threat and, eventually, the choices they make and the actions they take to ensure a livelihood for themselves and their families.

Reef managers should ideally see their work in this context to help face the challenge of understanding how their actions are likely to lead to a change in the options open to a range of different people within this complex, dynamic picture of livelihoods.





## Steve Box

Centro de Estudios Marinos

### RESEARCH

We are looking into improving the management of key reef fish species, specifically yellowtail snapper so as to help protect other ecologically important species such as parrotfish and commercially important species such larger-bodied groupers which have seen big declines in the abundance and diversity. Yellowtail snapper is at a really crucial point because it is one of the last commercially important species before fishers switch gear types to very unselective gears. The whole research works to provide tools for the region so that we can rebuild fish populations on reefs and have sustainable fisheries at the same time.



*Seen evidence of change on Caribbean coral reefs? Yes and no actually. Yes, there have been very widely documented declines that we all read about. Then in a local context, we've seen declines in diversity and abundance of fish. We do see these issues and there's been a lot of comments from fishers that we work with that it's getting harder to fish. They have to go further; the fish they are catching are getting smaller. They are shifting species; they are putting more effort in and getting less return. So we see that a lot; we hear that a lot and that's important because there's this kind of word-of-mouth - problems that it's really touching people's day-to-day lives.*

*In terms of the quality of reefs, we're losing coral cover. Visibility in the water's going down. Things you can really notice. But, as well there are some success stories. There are some areas where things are still very, very good and I think it's very easy to focus on the negative side and we do need to be aware of it, but it's not all doom and gloom. There are positive stories and I think it's very important that the work we do can make people change; can make positive change to the ecosystems and it's not too late for these proactive steps. It is not pristine; it is not in a wonderful state but it's not the end of the world. We can manage it.*

**it's not too  
late for these  
proactive  
steps ...**

1

Coral reef dependency  
and change: implications  
for the future



2

Livelihood enhancement  
and diversification to  
support adaption  
to changes in coral reefs



# Coral reef dependency and change: implications for the future

*Fresh catch on the fish market in Dieppe Bay, St. Kitts and Nevis.*

## THE EVIDENCE

Households in eight coastal communities across four countries (Barbados, St Kitts and Nevis, Honduras and Belize) were interviewed with the aim of understanding how people depend on coral reefs and how they have responded to change.

### Coral reef dependency

For many people coral reef dependence is directly or indirectly associated with either fisheries or tourism activities, or a combination of the two. These activities provide a source of income and employment and in the case of fisheries, provide food and have cultural significance.

### The variability of dependency

The nature of coral reef dependency varies from one household to the next. In certain locations, where the local economy offers few alternatives, coral reef dependency may be high. Dependency can vary throughout the year according to seasonal changes in accessibility and availability of fisheries resources and fluctuations in tourist arrivals. In addition, dependency varies unpredictably, with households suddenly relying heavily on coral reef fisheries as a safety net following unemployment in other sectors.

## THE ISSUE



*Throughout the Caribbean, people depend on coral reefs in many ways. This dependence makes them sensitive to changes in the availability of or access to the resources and services coral reefs provide. Such changes may take place seasonally, suddenly, or over generations. Understanding the sensitivity of livelihoods to these changes and the implications on people's livelihoods and their vulnerability is critical for informing policy and management decisions which affects access to coral reef resources.*



Many activities dependent on coral reefs are sensitive to sudden changes such as the hazards associated with fishing (e.g. bad weather, decompression sickness in lobster divers), the unpredictable nature of the tourism economy, or the impact of hurricanes. These are changes which households have little control over and can lead to the sudden loss of access to coral reef resources and related employment and income.

Long-term changes in dependency - for many households, declining fisheries availability and access has undermined their dependence, making livelihoods more insecure and less viable. In some cases, livelihoods have been criminalised, where fisheries or conservation restrictions have limited access to coral reef resources, and households are unable, or unwilling, to access alternatives.

At the same time, a growing tourism economy has led to increasing dependence on coral reef associated tourism, through a range of employment opportunities. The growth of tourism is also, in some cases, a driver of continued fisheries dependence, offering a lucrative market for fish products with high returns for fishers. The demand for fish from tourist restaurants and hotels can divert fish supplies away from local markets, potentially reducing food security for local people.



Dive school in Utila, Honduras.

### Coral reefs as a safety net

*The accessibility of near shore coral reef resources often means people turn to them during sudden periods of hardship. In St Kitts and Nevis, case studies revealed households which had been forced to depend heavily on coral reef fisheries following loss of employment in the construction industry. Likewise, on the island of Utila in Honduras, mainland Honduran migrants were reported to fall back on the near shore coral reef fisheries when they found themselves out of work.*

### Changing fishing practices

*Across all countries studied, fisher households have been attempting to cope with the declining availability of fisheries by modifying their fishing practices. This may mean increasing the time spent fishing, travelling to new or more distant fishing grounds, or making use of new technologies. However, for many fishers rising fuel prices have limited the success of these changing practices, and they continue to face declining returns.*

### Coping with changing dependency

Households adopt a range of different strategies to respond and cope with changing access to and availability of coral reefs. These strategies include modification of existing activities, diversification or substitution of activities, and even migration. Diversification presents a key strategy, helping households cope with seasonal, sudden and long term changes by providing income sources from different sectors, such as tourism, farming and construction.

The growth of tourism has presented many opportunities for diversification, but the finance and skills required are not always easily accessible to local people and some tourism activities, such as SCUBA diving, are often dominated by outsiders with more resources. Tourism opportunities have allowed many households to diversify and improve their livelihoods, alleviating the insecurities of fisheries dependence in the short term. However, these new opportunities are still vulnerable to degradation of the coral reef and the uncertainties of wider economic and political changes.



## MANAGEMENT IMPLICATIONS

### Factoring coral reef dependency into decision making

Any management intervention that limits access to coral reef resources, such as no-take marine reserves, will have social and economic impacts on people who depend on coral reef resources for their livelihoods. Policy and management decisions should ideally factor in an understanding of the varied nature of dependency on coral reefs, recognising the seasonality of this dependency, as well as the role of coral reefs as a safety net for households.

### Help people adapt and build resilience

Acknowledging that change and uncertainty are a central and continuing part of people's lives, it is important to help build people's resilience and capacity to adapt to future changes and not just in relation to current conditions. People's on-going experiences of responding to change needs to be central in this effort, building on their existing capabilities and their visions for the future. To succeed in supporting households build resilience for an uncertain future, policy decisions are best if they are adaptive and integrated across sectors, recognising that people's livelihoods draw upon multiple sectors, from fisheries and tourism to farming and construction.

## Livelihood enhancement and diversification to support adaptation to changes in coral reefs

Fruit stall in St. Kitts and Nevis.

### THE EVIDENCE

A series of interviews and workshops with individuals, households and key informants were conducted in 8 communities across four countries (Barbados, St Kitts and Nevis, Honduras, and Belize). Questions and discussions focused on understanding people's responses to changes to help identify key guidance for supporting future livelihood change. Additionally, a workshop brought together people from around the Caribbean with experience in supporting livelihoods change.

### KEY FINDINGS

#### Adaptation to change is a way of life

People in the Caribbean already constantly adapt and respond to changes such as seasonal changes in weather, sudden shocks from hurricanes, changes in the demand for tourism services and wider economic fluctuations, and new measures (e.g. MPAs) that restrict access to coral reefs. Climate change is making adaption even more challenging.

#### Matching skills, existing capacity and market demand

In Honduras, skills training provided to households through a poverty alleviation fund had relatively limited success in supporting long-term livelihood change. The skills provided did not match or build on existing capabilities or market demand and training was not supported by measures to assist people to start up new businesses to make use of the skills they had acquired.



*When people's ability to make use of coral reefs and the services that reefs provide changes, their livelihoods are impacted. The way people use these resources to obtain food and income and their social and cultural activities can all be affected. This is true whether the changes take place because of declining reef health, or whether they are a side-effect of measures introduced to protect coral reefs by limiting people's access and use, e.g. marine reserves.*

*Encouraging people to take up new, or 'alternative', livelihood activities is often regarded as an important means of reducing human pressure on reef resources. However establishing genuinely sustainable alternative livelihood activities that respond to people's aspirations in the long-term has often proved challenging.*



### Appropriate and adaptable support

Having access to the right kind of institutional support in order to identify and take advantage of new opportunities is also important. This includes access to credit or grants and training in new skills, as well as access to information about livelihood opportunities, new markets and the experiences of others. People often draw on support from a range of organizations and institutions in order to obtain these.

### Livelihood adaptation

The timeframes involved in building more adaptable and resilient livelihoods are long, often involving generations.

### Building on skills and networks

To adapt, people draw on their existing skills, knowledge and resources, enhancing existing activities and diversifying into related activities, e.g. for fishers in Belize, shifting over to guiding tourists visiting coral reefs enabled them to make use of their existing knowledge of the marine environment. Social networks of family, friends and connections are a key source of support. Remittances from family members abroad are playing an increasingly crucial role.

### Drawing on diversified support for livelihood change

*People draw on diverse sources of support to successfully change their livelihoods. A food vendor in St. Kitts started her business by combining existing skills with a compensatory financial package provided when she lost her job at a local resort. A seaweed farming initiative by a local cooperative in Belize built on experience in wild seaweed collection among the members as well as support from local institutions. Local organizations also played an important role in another Belizean initiative to develop cultural tourism driven and owned by indigenous garifuna people.*



Seaweed farming.



Cruiseship and dive boat in St. Kitts and Nevis.



Boys with cast seine net.

## MANAGEMENT IMPLICATIONS

### Allow time for livelihood change

Some of the best cases of successful support for livelihood adaptation come from longer-term interventions, particularly where local organizations rooted in the community have taken the lead.

### Empowering people to make their own decisions about livelihood change

Empowered individuals and communities are more likely to develop viable strategies for the future than those who have been provided with ready-made, 'off-the-shelf' solutions by outside agencies. In a dynamic environment, where no single livelihood option is likely to remain viable for long, developing people's capacity to adapt now, and in the future is important.

### Building adaptive capacity

More attention needs to be given to building people's capacity to make changes in their livelihoods before changing circumstances reduce their capacity to respond. For example, where reef management measures are being introduced that will restrict people's access to reef resources, the reef users' capacity to adapt to new restrictions needs to be built before those measures are introduced, so that they are in a better position to take changes in their stride.

### Creating supportive networks

To support long-term processes of livelihoods change, and to make those processes sustainable, the focus should be on establishing supportive networks that ensure that people have access to the information, skills, resources and technical support that they need. Supportive networks need to be adaptable, capable of providing long-term support, and involve a range of agencies that can respond to people's diverse needs.

# Reef Monitoring for Management



*Monitoring the state of the reef is often a fundamental part of any reef management programme. Many different methods, such as AGRRA and CARICOMP, are used to survey reefs, but collecting data is only useful if the trends observed can be interpreted.*

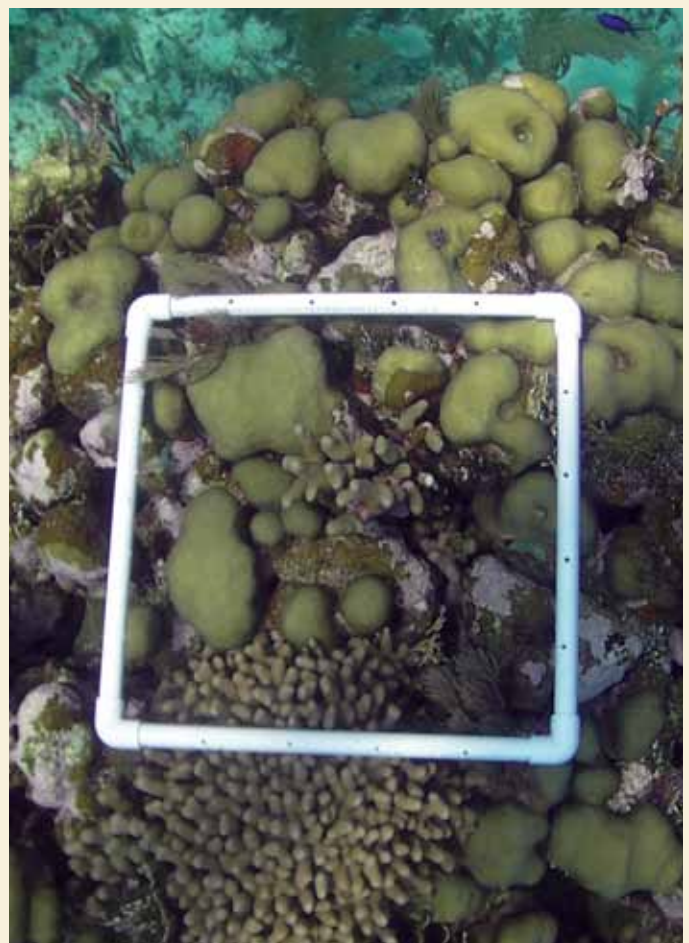
*Frequently asked questions include:*

*Are some trends OK whereas others are a cause for concern? What does a particular trend tell me?*

*What kinds of management measures should I consider in light of certain patterns?*

*Are there any threshold values of say, coral cover that I should be worried about crossing?*

*We try to answer these to the best of our ability, drawing on the wider scientific evidence to date.*



*Benthic photo quadrats are commonly used in reef monitoring.*

## WHY MONITOR REEFS?



Recording reef fish on a survey in Tobago.

Most reef management programmes need to conduct some form of monitoring. The objectives of each monitoring programme may vary, but most attempt to determine the current health of the reef as characterised by variables such as coral cover and fish biomass. The core objectives of monitoring usually include:

- To provide an early warning system of stressors on the reef system
- To help diagnose potential causes of reef degradation and identify appropriate management methods to combat the causes
- Determine if reef management measures, such as MPAs and restrictions on tourist activities, are having an effect.

Reef monitoring is not the only reason to undertake reef surveys; rapid assessment of reefs is frequently carried out to compare

the vulnerability of reefs or to prioritise sites for conservation activities. Although rapid assessment uses snapshot surveys rather than repeated sampling over time (monitoring), many of the same techniques and principles apply.

This following information is not intended to provide a step by step guide for reef monitoring, particularly given that many texts exist on methods. Instead we focus on three areas that we hope will be of use to reef managers:

1. Overview of current reef survey methods and programmes available
2. Practical advice on which methods to use and key considerations on implementing them
3. Detailed guidance on interpreting results gained from reef monitoring.

Protocol (purpose)	Community surveyed	Method	Number of transects and dimensions	Detail recorded	Data analysis methods included?	Methods available freely online?
AGRRA (structural and functional attribute of reef, fisheries independent data)	Benthic	Point intercept transect	6 x 10m transects, 10cm intervals	Benthic species or category, including coral state (bleached, newly dead)	No. But rationale given for each included species and method. Data to be sent to AGRRA database.	Yes: <a href="http://www.agrra.org">www.agrra.org</a>  Manual, data entry sheets and training materials all available online.
				Macroalgae (cyanobacteria and turf) height		
		Quadrats	5 x 25cm x 25cm on each transect	Coral recruits (<2cm)		
				Predominant substrate type		
		Belt transect	6 x 10m x 1m	Diadema, spiny lobster, queen conch, lionfish, rubbish		
				Predominant algae		
	Coral	Belt transect	2 x 10m x 1m	Corals >4cm species, state, dimensions, % mortality/ bleaching		
CARICOMP (productivity structure and function)	Benthic	Chain transect (laid below 10m taut transect line)	10 x 10m permanent transects, measured once a year	Benthic species or category, coral growth form	No. Data to be sent to CARICOMP.	No. But manual can be requested through CARICOMP.
		Gorgonians	As above	Gorgonian species and growth form		
		Diadema	As above x 1m	Diadema count (+ other urchins)		
	Fish	As AGRRA				
Reef Check (community engagement and volunteer coral reef monitoring)	Benthic	Point intercept transect	20m, 0.5m interval	Substrate categories (x 10)	Yes – integrated into Excel spreadsheet. Data sent back to Reefcheck.	No. Training through Reef Check trainers
	Fish	Belt transect	4 x 20m x 5m	Commercially important species abundance of families, groupers and Nassau grouper in size classes		
	Invertebrate	Belt transect	As above	Few indicator species + bleaching, coral damage impacts		

continued on next page

## METHODS FOR SURVEYING CORAL REEFS

Several different methods exist for surveying coral reefs. Programmes such as AGRRA (Atlantic and Gulf Rapid Reef Assessment) and CARICOMP (Caribbean Coastal Marine Productivity) have issued manuals which provide full descriptions of the methods used. Other manuals exist which provide details of a selection of methods and offer some advice on how best to conduct reef surveys, e.g. English et al. 1997 and Rogers et al. 1994. Some points to note regarding these manuals and programmes are:

- Rogers et al 1994: Very useful overview of methods available and Caribbean-focused examples
- English et al 1997: Comprehensive, though strong focus on Indo-Pacific reefs and methods. Includes methods for monitoring of mangroves, seagrasses, soft-bottom communities and coastal fisheries.

- CARICOMP: Very detailed methods, particularly use of chain transects, which are time consuming and not widely used for assessment (though still used for monitoring in places). Includes methods for monitoring mangroves and seagrass communities.
- AGRRA: Excellent set of techniques and you can pick and choose which to include. Basic and advanced versions allow for tailoring of methods to the expertise of the people doing the surveys.
- Reef Check: OK for basic data on fish abundance and benthos and for engaging community, but not designed as a monitoring tool.

For an in depth review of coral reef monitoring methods see 'Methods for ecological monitoring of coral reefs' by Hill and Wilkinson, available free online via the IUCN library system: <https://portals.iucn.org/library/dir/publications-list>



Laying out a transect line.

Protocol (purpose)	Community surveyed	Method	Number of transects and dimensions	Detail recorded	Data analysis methods included?	Methods available freely online?
English et al. 1997 (baseline assessment methods)	Benthic	Manta tow	Large scale (entire islands)	% cover of major categories (e.g. coral, sand, COTS)	Yes. Full rationale given for each method and data analysis suggested methods. Section on sampling and database design.	No.
		Line intercept transect	5 x 20m at shallow and deep	Benthic categories and species		
		Permanent quadrat (photo) + sediment trap	2m x 2m quadrat (in conjunction with LIT) at 3m depth	Detailed change in coral colonies and coral recruitment, measurements of coral colonies taken (tagged colonies)		
	Fish	Belt transect	3 x 50m x 5m transects, 2 depths	Selected fish species (fishery target, indicators, etc.), abundances binned, size estimation discussed		
	Coral	Recruitment tiles	12cm x 12cm tiles on wire rack, 20 -30 per site, multiple times per year	Coral recruits abundance, species		
	Reef fish recruitment	Belt transect	3 x 50m x 2m transects at each site	Reef fish recruits (only conspicuous, abundant juveniles surveyed)		
Van Woesik et al. 2009 (repeated measures of process and state variables)	Benthic	Transects and quadrats (both photo)	5 x 50m transects at each station; 3 x 4m x 4m quadrats at each station	Benthic composition and coral demography: size measurements, partial mortality	Some. Only instructions for photo quadrat analysis provided.	Yes: <a href="http://www.gefcoral.org">www.gefcoral.org</a>
	Coral	Quadrats and tiles	Quadrats as above	Coral recruits abundance, size and species		
		Belt transect and tagged colonies	3 x 10m x 2m transect at each station	Coral disease prevalence, progression		
	Fish	Belt transect	5 x 30m x 4m	Reef fish (adults)		
		Belt transect	8 x 40m x 1m x 1m	Reef fish (recruits)		

## KEY POINTS TO NOTE WHEN DESIGNING A MONITORING PROGRAMME

### State variables and process variables

- State variables, as the name suggests, give you information on the current state of the reef, such as coral cover, abundance of fishes, macroalgal cover.
- Process variables provide information on the ecological processes that drive the state variables. Key process variables that might be measured include recruitment rates, growth and survival rates and herbivory. Measurement of process variables can be important for diagnosing the potential causes of reef change and can provide information on the future trajectory of the reef.

### Stratification of habitat

What is referred to as coral reef is made up of several different habitats, such as gorgonian plains, patch reefs and *Orbicella* dominated forereefs. The physical, biological and chemical processes that drive the ecology of these habitats can be quite different. Stratifying surveys according to habitat as well as other factors, such as wave exposure and proximity to river outflows is important to avoid comparing results from reefs that are fundamentally different. For example, healthy *Orbicella* dominated forereefs should have high hard coral

cover, whereas healthy gorgonian plain habitats naturally have very low hard coral cover. Averaging data from both these habitats would result in a misleadingly low value for coral cover, because only one habitat has significant coral in its natural state. It is particularly important to discriminate flat featureless gorgonian plains from degraded examples of true 'coral reef' habitats that have lost their complexity. Typically gorgonian habitats are found in more exposed environments and have fine layer of sand sitting above the hard substratum.

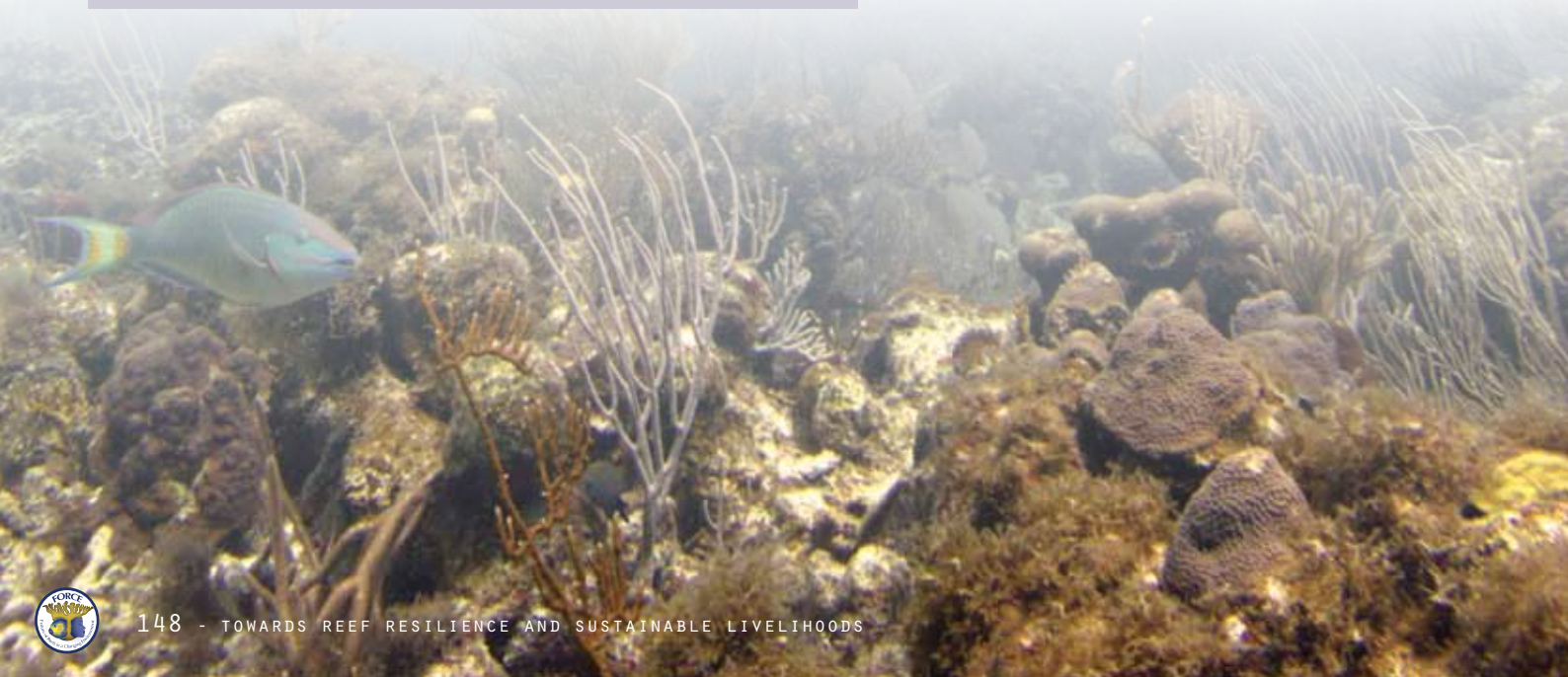
Classification of reef habitats is generally based on their physical and biological features including the dominant species and reef geomorphology. One example of a classification scheme, describes the eleven common reef and lagoon habitat types found in the Bahamas (Table p.149). Although this classification scheme does not cover all habitats found in the Caribbean, it does provide a starting point for managers wishing to form their own classification scheme.

Habitats can be mapped using a combination of remote sensing methodologies. Direct mapping is often carried out using high resolution satellite imagery. Distinguishing areas of forereef that are dominated by gorgonians versus coral reef habitat (*Orbicella* reef) can be carried out cheaply and reliably using the simple relationship described by Chollett and Mumby (2012) and wave exposure data available via the FORCE WebGIS, link available through: <http://force-project.eu>








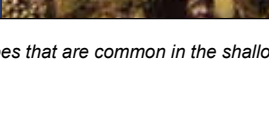
A complete map of the physical environments of the Caribbean Sea is also available (Biogeography Brief 1 p.22), which can also be used to help stratify monitoring sites.

### Free resources to help map coral reef habitats

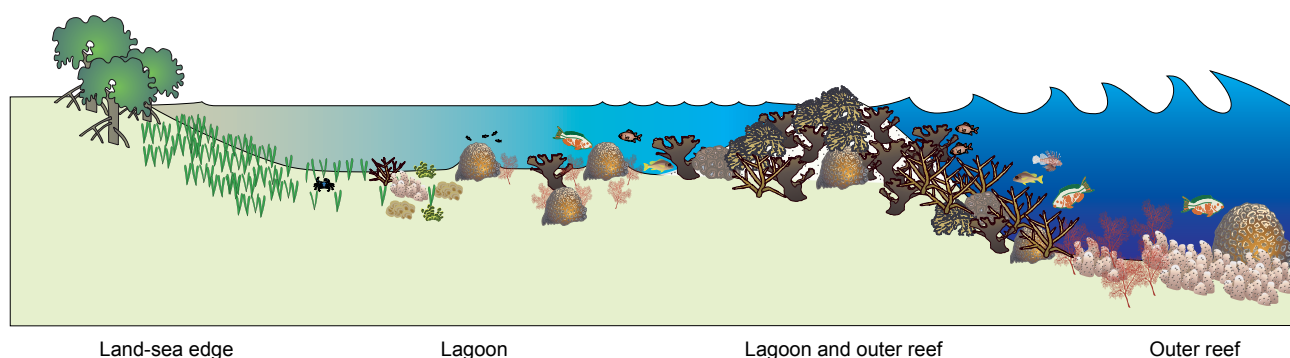
- The 'Remote Sensing Handbook for Tropical Coastal Management' is available for free download through the FORCE website or by contacting Prof Peter Mumby ([p.j.mumby@uq.edu.au](mailto:p.j.mumby@uq.edu.au)).
- Free and excellent software for remote sensing is available online together with specific training modules for coral reef management applications. See Bilko for Windows <http://www.learn-eo.org/software.php>
- An online directory of remote sensing applications and toolkits for coral reefs is available from [www.gefcoral.org](http://www.gefcoral.org) (see remote sensing publications).



## COMMON REEF AND LAGOON HABITATS

Habitat type			Description	Examples of ecological functions
Land-sea edge		Fringing Mangrove	Outer edge of red mangrove stands. Found along shorelines, tidal creeks, offshore islands.	Habitat for spiny lobster, Nassau grouper, and invertebrate-eating fishes. Moderate contributions to primary productivity.
Lagoon		Dense Seagrass	Dominated by turtle grass but may contain manatee grass.	Converts atmospheric nitrogen into biologically useable form (nitrogen fixation). Habitat for spiny lobster, queen conch, and invertebrate-eating fishes.
		Medium-density Seagrass	Dominated by turtle grass but may contain manatee grass and shoal grass.	Converts atmospheric nitrogen into biologically useable form (nitrogen fixation). Habitat for spiny lobster, queen conch, invertebrate-eating fishes, and <i>Euchema</i> seaweed.
		Sparse Seagrass	Dominated by manatee grass and shoal grass.	Habitat for queen conch and <i>Euchema</i> seaweed
		Sand and Sparse Algae	Sand with sparse algal community.	Habitat for queen conch
		Patch Reef	Dominated by massive corals and dense sea fans (gorgonians).	Habitat for surgeonfishes, long-spined sea urchin, stoplight parrotfish, threespot damselfish, young coral, invertebrate-eating fishes, and spiny lobster.
Lagoon & Outer Reef		Seaweed Plain	Relatively smooth, rocky bottom with seaweeds and few sea fans (gorgonians).	Habitat for spiny lobster and Nassau grouper. Fuels food web through primary productivity. Converts atmospheric nitrogen into biologically usable form (nitrogen fixation).
Outer Reef		Elkhorn Coral	Reef-crest areas between depths of 1-5 meters.	Fuels food web through primary productivity. Habitat for surgeonfishes, long-spined sea urchin, and stoplight parrotfish. Forms reef structure (calcification). Converts atmospheric nitrogen into biologically usable form (nitrogen fixation).
		Dense Gorgonians	Densely covered with sea rods, fans, and other gorgonians with little hard coral. More than 10 gorgonians per square meter. Often just seaward of elkhorn coral reef; also in shallow, wave-swept areas.	Fuels food web through moderate levels of primary productivity. Habitat for spiny lobsters, Nassau grouper, reef-grazing organisms, plankton-eating fishes, and invertebrate-eating fishes. Moderately vulnerable to bleaching and disease.
		Gorgonian Plain	Sparse sea rods, fans, and other gorgonians on hard, rocky bottom with some seaweed.	Habitat for Nassau grouper, surgeonfishes, long-spined sea urchin, and invertebrate-eating fishes. Vulnerable to disease.
		Orbicella reef	Dominated by star coral. High structural relief. Typically in areas relatively sheltered from waves.	Habitat for stoplight parrotfish, threespot damselfish, surgeonfishes, invertebrate-eating fishes, young coral, long-spined sea urchin, spiny lobster, and Nassau grouper. Forms reef structure (calcification). Converts atmospheric nitrogen into biologically usable form (nitrogen fixation).

Eleven habitat types that are common in the shallow coral reefs and lagoons of The Bahamas.



Land-sea edge

Lagoon

Lagoon and outer reef

Outer reef

## TIPS FOR SURVEY METHODS - BENTHOS

### How to measure?

#### Quadrats

- Usually 1 m<sup>2</sup> with 10 cm nylon grid.
- Typically 20+ per site.
- Can be photographed for later analysis or percentage cover can be estimated *in situ*
- In addition, measure the canopy heights of major forms of algae using a ruler (3 measurements per quadrat).
- For juvenile corals use 25 cm x 25 cm quadrat, ten per site, placed only on hard substrate, free of living adult coral.



#### Line intercept transects

- An alternative to quadrats.
- Typically 10 m length weighted transect tape with marks every 10 cm.
- Usually 3-4 transects per site.
- Benthic cover recorded directly below tape and composition of each 10 cm segment recorded.
- Measure algal canopy and height several times along transect.



#### Video transect

- An alternative to quadrats or line intercepts transects but not great for small corals.
- Video of a swath of reef taken adjacent to a transect line.
- Distance of camera from reef varies the width of transect: short distance (15 – 20 cm) recommended for detailed surveys (i.e. species level ID), larger distance (40 – 50 cm) for larger scale surveys (e.g. effects of bleaching).
- Typically five 50 m transects or ten 10 m transects per site.
- Video broken into non-overlapping photo frames for analysis.



#### Rugosity

- Use a 5 m chain and planar transect tape to measure the horizontal distance which the chain has covered.
- Calculate rugosity as length covered by taut transect tape divided by distance covered by chain, e.g. 5 m chain may fit to the substrate and cover only 2.5 m horizontal distance ("as the crow flies"); rugosity =  $5/2.5 = 2$ .
- Use at least 4-5 random transect measurements per site.

### Software for analysis of photo quadrats or video frames

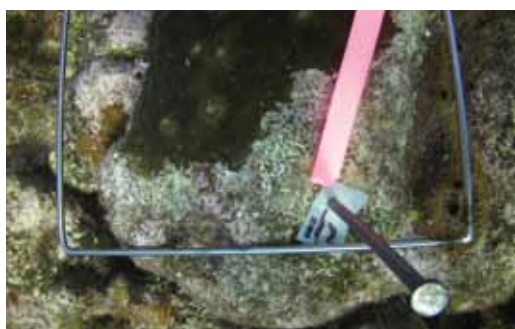
Analysis of photo quadrats or video frames can be easily done using the following software packages:

- **VidAna** – simple, free software for quantifying percentage cover by drawing around different benthic categories:  
<http://www.marinespatialecologylab.org/resources/vidana/>
- **ImageJ** – another free software package that can be used to quantify percentage cover by drawing shapes around benthic organisms and substrate, but requires slightly more technical knowledge:  
<http://imagej.nih.gov/ij/>
- **Coral Point Count** with Excel extensions – specifically designed for determining benthic cover from reef transect photos. Software generates random points over photo and the user then identifies the features under these points: <http://www.nova.edu/ocean/cpce/>

It really does not matter much whether you choose quadrats or line transects. Photo and video transects provide a permanent record. However, it is important to remember that analysis of videos and photos can be time consuming. Photo and video transects/ quadrats also have the advantage that more in-detail analysis can be done at a later date (e.g. if initial analysis of a video transect only recorded a single category for hard coral cover, later analysis could still be done to distinguish cover of individual species).

### Permanent sample units?

If a one-off reef assessment is being done, then there is no need to implement permanent quadrats or transects. For monitoring, there are advantages to fixing the corners of quadrats and ends of transects because this provides greater statistical power for the same number of samples, i.e., it's more likely you'll detect a trend in the data. Plastic or stainless steel pegs are best used to mark quadrats or transects as iron pegs or rebar can rust, causing localised algal blooms that can distort the data.



### What to measure?

This will depend on the objective of the monitoring programme or assessment, however core measurements include:

- Coral cover - ideally by species
- Cover of major algal groups - crustose corallines, turf, fleshy macroalgae, *Lobophora*, *Dictyota* spp, articulated corallines (e.g., *Halimeda*).
- Canopy heights of algal turfs, fleshy macroalgae, *Dictyota*, *Lobophora* and articulated corallines – average height can be calculated and multiplied by the cover to obtain a volumetric index of algal abundance that is more likely to be insightful than cover alone.
- Sponge cover – especially *Clionoids* ([Resilience Brief 7 p.46](#))
- There really is not much need to include sand/ sediment but if you do include them ensure that their cover is excluded from the calculation of percent coral and algal cover because this substrate is not available for reef colonisation and is therefore of little relevance.
- Urchin density – typically within ½ m either side of a 10 m transect line. Separate *Diadema* and *Echinometra*.
- Rugosity ([see How to measure? p.150](#))
- Juvenile coral density – count juveniles (corals up to 2 cm diameter). For density calculation only include the percentage of space available for recruitment, i.e. exclude live coral cover.
- Diseases - it is more useful to monitor the incidence (percentage of new infections per year) and fate (probability coral survives) of disease rather than simply prevalence (percentage of corals that have a disease whenever a survey is done). Taking an extreme example, imagine that 5% of corals get infected by the disease a year and then die quickly. The prevalence might remain stable for a while (5%) but there'd be no corals left after a number of years. Alternatively, 5% of corals might have the disease and manage to cope without dying. The incidence of new diseases could be virtually zero, which is a far better state of affairs. But in these contrasting cases the prevalence would be the same and not alert you to a major problem. Incidence can be studied by tagging a random number of corals and following their fate over time.
- Coral bleaching - observations of bleaching are important but remember that many corals completely recover when the bleaching event has past, particularly if the stress was minor or shortlived. It's useful, therefore, to tag a bunch of random colonies (e.g., 50 per site bleached or not) and track whether they survive or not, or how much coral is lost (partial mortality).

### Physical factors

#### Sediment

If a sediment problem is suspected it is useful to set up sediment traps. Sediment traps are frequently misused, providing misleading data on sedimentation rates. Storlazzi et al. (2011) provides more information on using sediment traps on coral reefs, including nine basic protocols to follow.

#### Nutrients

Where raised nutrient levels are suspected as an issue on a reef, analysis of algae samples can help in the diagnosis. Samples should be taken along a gradient: from areas which are believed to be highest in nutrients to those that are the 'cleanest'. The species of algae to be sampled will depend on what is available at the sites, but where there are algal blooms, it would be most logical to sample the most abundant species. Only small samples (less than 1g) are required for analysis, but at least 5 samples per site for each species should be taken. The apical section (growing tip) of the algae is the place to sample. Samples should be air or oven dried, then ground to a powder. In most cases, samples will have to be sent to a laboratory for nutrient content analysis, so it is best to confirm with the lab how they prefer the samples to be prepared. This analysis should be contrasted with analysis of dissolved nutrients in the water.

Isotope analysis of algae samples can help identify the source of nutrients, e.g. fertiliser run-off, sewage, factory effluent, and therefore target where management measures would be best focused.

## TIPS FOR SURVEY METHODS - REEF FISH



*Hogfish.*

### Who will measure?

There are enormous differences in data between observers even if they are experienced and using the same technique. This occurs because people swim at different speeds and differ in their decisions over whether to include a fast-moving fish passing across the transect ahead of them. So, if possible, try to use the same person for all fish surveys – or at least all surveys of a particular fish group.



*Tiger grouper.*

### How to measure?

There are two main quantitative methods available – stationary sampling of fish within a cylinder around the diver (Bohnsack and Bannerot 1986) or the laying of belt transects. Either are fine although transects have become more widely used so might be easier to make comparisons with other datasets. We focus here more on transects.



*Rainbow runners.*

### Transect size and number

We generally find it most effective to scale the size of the transect to the habitat and abundance of the fish group. For example, damselfish and wrasses are found in high densities and can be adequately surveyed using 30 m x 2 m transects ( $n=4+$ ). Parrotfish and grunts can be surveyed using wider transects (we use 30 m x 4 m,  $n=10$ ), whereas grouper, snapper and jacks are better censused using 50 m x 4 m transects ( $n=5+$ ). If a single person is conducting the census then consider using a 30 m transect and surveying the widely-roving and rarer species within a 4 m swath and then return along the transect and sample the high-density, small species along a narrower 2 m swath.



*Trumpetfish.*

### Abundance of rare species

The density and biomass of those species that tend to be very rare, such as large groupers and sharks, are often not well represented using standard transect or cylinder methods. There are two solutions to this. One is to use timed swims, such as 5 minute long swims at a particular depth, recording everything you

see. The other is to just record whether you see these species (and their size, etc) when doing regular transects. In other words, they might not appear on the transect but you might observe them during the dive. The advantage of the latter approach is that it standardises the area surveyed and time quite well. The data are then used to estimate the probability of seeing the species per survey (e.g., per hour of fish census) rather than an actual density. For example, if you saw a shark on 2 out of 20 surveys, then the probability of occurrence / encounter is 10%. You can test for significant trends over time using the binomial distribution (see examples in Mumby et al. 2004; Mumby et al. 2012).

For these rare species, fixed video cameras can be used as they can be left running for extended periods of time (4 hrs +). This is possible even with limited funds thanks to the availability of cheap, high quality cameras such as GoPros. It is important to remember that all footage will need processing!

### Fish biomass

It is important to estimate the size of fish so that trends can be tracked (e.g., is fishing pressure so high that average fish size is getting smaller?) and biomass can be estimated. Biomass is the usual currency for assessing patterns in reef fish assemblages. Several protocols suggest that fish sizes are placed in bins (e.g., 1-5 cm, 6-10 cm, etc). This is an unnecessary simplification and weakens the data analysis because it is not straightforward to interpret a trend in the number of fish in a size class (e.g., size could be decreasing within a class but this would be undetected). Better to attempt to estimate size to the nearest centimetre and use a T-bar to help scale observations when in the field. If necessary, actual measurements of size can be regrouped into bins at a later date for comparisons to datasets where bins are used. Lengths can be converted to biomass using a simple equation that requires two parameters per species (Bohnsack and Harper 1988, Fishbase.org).

### What to measure?

This depends on the objectives of the monitoring programme, but the following is a minimal list to consider:

- Commercially important species – groupers, snappers, barracudas, large-bodied jacks, large wrasses such as Hogfish
- Ecologically important species – parrotfishes (preferably distinguishing between terminal and initial phases), surgeonfishes, damselfishes, triggerfishes, porgies, trumpetfishes, smaller groupers, lionfishes.



## TIPS FOR SURVEY METHODS - SHELLFISH

**Spiny lobster (*Panulirus argus*)**

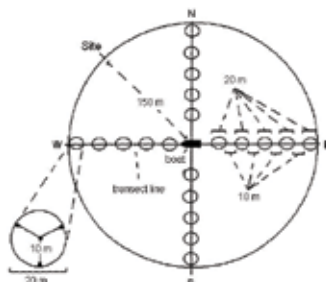
As with conch, lobsters are often recorded as part of standard benthic survey protocols. However, for lobster-specific censuses the survey methodology must take into account the fact that lobsters are nocturnal, remaining hidden under ledges and in crevices in the reef during the day. As such, belt transects or timed searches by SCUBA divers are most commonly used but require careful inspection of shelter habitat. Manmade aggregating shelter devices or baited traps may also be deployed for fishery independent lobster surveys. Apart from the number of lobsters encountered, surveys may also record size (e.g. carapace length), sex and the reproductive status of females (e.g. whether berried with eggs or carrying a sperm filled tar spot). Sites are normally stratified by habitat and depth. For deep water, traps are the only practical option for obtaining an index of abundance.

**Belt transects**

Vary in size, but can be between 50 and 150 m long depending on habitat and up to 10 m wide (Smith & van Nierop 1986; Acosta & Robertson 2003).

**Timed search**

Commonly 3 x 1 hr searches per site (Bertelsen & Matthews 2001; Cox & Hunt 2005), timed searches yield relative abundance (number of lobsters per unit time) compared to belt transects which yield density estimates (lobsters per unit area). As lobsters are gregarious and their distribution is often patchy, timed searches are often the better method of surveying (Cox & Hunt 2005).



Layout of circular transects used for surveying conch.

**Queen Conch (*Strombus gigas*)**

Conch are often recorded in standard reef monitoring programmes as part of the benthic survey protocol, e.g. AGRRA. For specific conch surveys, typically either belt or circular transects are used depending upon conditions. The number of conch, habitat type and depth of observations are typically recorded on all surveys. Other attributes such as shell length, lip thickness and spawning behaviour may also be recorded on surveys which allow the surveyor to stop (i.e. not towed or scooter surveys).

**Belt transects**

If a large shallow sandy area is to be covered and it is relatively calm with good visibility, then belt transects are typical and are usually done by towed free diver. If deeper, but still relatively calm, then towed SCUBA diver or a SCUBA diver left to swim the benthic transects with underwater scooter (for examples see Tewfik et al. 2001) or unassisted (for examples see Stoner and Ray 1996) may be used. For water deeper than safe diving depth (e.g. > 30 m) remotely operated underwater vehicles (ROVs) may be used. Transects vary in length and width depending on the size of area to be covered; however they are generally 2 – 5 m wide.

**Circular transects**

If areas are smaller, or have complex topography (e.g. reef), or highly variable depths, then circular surveys work much better. This is also a good method if sea conditions are rough and you don't want divers scattering in all directions from the support vessel! For this method you have a central marker and a rope (or tape) attached to it, and you swim in circles moving further away from the centre. This allows a much more detailed search. Circle radius has varied among studies from 7 to 20 m. This method has been used in Jamaica (Tewfik & Appeldoorn 1998), Bahamas (Stoner et al. 2012) and around Barbados (Valles & Oxenford 2012).

For deep water, an underwater drop video camera can be used.

For a good description of sampling design for conch surveys see 'Conch (*Strombus gigas*) stock assessment manual' by Erhardt and Valle-Esquivel, available via the Caribbean Fishery Management Council website: <http://caribbeanfmc.com>

# INTERPRETING REEF MONITORING DATA

There are two aspects to interpreting monitoring data. The first is simply how the data should be analysed. We do not cover this here as there are many resources available on this topic. A particularly good text is: 'Practical statistics for field biology' by Jim Fowler and Lou Cohen.

The second issue is how to interpret the trends found in the data. We have attempted to provide some guidance on this issue for the most widely-used monitoring variables. For each variable, we considered how to interpret changes in variables, what other variables could be looked at to provide more information and the ecological implications of the change.

**Acute decrease/ increase – normally greater than 10% in a year**

**Chronic increase/ decrease – few % per year**

## FISH/SHELLFISH



**Total fish abundance**

*What is the trend?*

**Decrease**

*Possible main interpretation*

Difficult to interpret change, check length data, possibly: increase in fishing pressure (reduction in abundance of large fish) or loss of habitat (reduction in abundance of all size classes).

*Other variables to look at*

Fisheries data, species level length data, rugosity (has it declined?).

*Ecological implications*

General loss of reproductive capacity and fisheries productivity.



**Total fish biomass**

*What is the trend?*

**Decrease**

*Possible main interpretation*

Decrease in average fish size and/ or abundance due to: increasing fishing pressure (reduction in abundance of large fish) or loss of habitat (reduction in abundance of all size classes).

*Other variables to look at*

Fisheries data, species level length data, rugosity.

*Ecological implications*

General loss of reproductive capacity and fisheries productivity.



**Groupers and snappers biomass**

*What is the trend?*

**Decrease**

*Possible main interpretation*

Overfishing.

*Other variables to look at*

Abundance and size data, fisheries data.

*Ecological implications*

Loss of top predators; trophic cascade effects.



**Fish diversity (species richness)**

*What is the trend?*

**Decrease**

*Possible main interpretation*

Loss of species, possibly due to habitat loss.

*Other variables to look at*

Species level biomass data.

*Ecological implications*

Loss of functional redundancy in specific groups which could reduce resilience as fish feed less extensively.



**Lionfish density**

*What is the trend?*

**Increase**

*Possible main interpretation*

Lionfish population has not reached maximum density.

Note that a decrease can occur even in the absence of control measures because the population might exceed its carrying capacity – effectively running out of food (though not yet described for lionfish).

*Ecological implications*

Reduction in biomass of prey species (small fish species and juveniles), possible reduction in reef resilience if prey upon herbivores.

*Supporting references on page 159.*



**Grunt biomass**

*What is the trend?*

**Decrease** (when they are not a targeted fishery species or caught as bycatch in traps). If they are fished, then fishing can be a driver of decline.

*Possible main interpretation*

Loss of nursery habitat (mangroves and seagrass) and/ or foraging grounds (seagrass and sand flats).

*Other variables to look at*

Fisheries data (check for absence of grunts in catch), habitat survey data.

*Ecological implications*

May indicate loss of mangrove/ seagrass habitat which both play important functional roles.



**Damselfish density**  
(three-spot, longfin and dusky)

*What is the trend?*

**Increase or decrease**

*Possible main interpretation*

Decrease can follow an increase in abundance of their predators (mainly mesopredators) due to fishing down the food web. Loss of preferred habitat could also be a factor (e.g., loss of living *Acropora cervicornis*). Increase in damselfish abundance might occur if predators decline.

*Other variables to look at*

Biomass of mesopredators, coral species composition.

*Ecological implications*

An increase in these damselfish can result in an increase in algal turfs – can have negative impacts on coral recruitment.



Parrotfish biomass

*What is the trend?*

### Increase

*Possible main interpretation*

Unless fishing recently declined, an increase is usually attributed to a large loss of coral and increase in algal food.

*Other variables to look at*

Coral cover, trends in fishing.

*Ecological implications*

Helps compensate for the loss of coral in reducing potential algal bloom.



Trigger fish and porgies biomass

*What is the trend?*

### Increase or Decrease

*Possible main interpretation*

Increase implies overfishing of predators in a system where triggerfish and porgies are not heavily targeted.

A decrease implies direct fishing effects.

*Other variables to look at*

Biomass of predators, turf/macroalgal cover.

*Ecological implications*

A reduction in their biomass could lead to increased *Diadema* densities and vice versa.



Barracuda and jacks biomass

*What is the trend?*

### Decrease

*Possible main interpretation*

Overfishing most likely explanation.

*Other variables to look at*

Abundance and size data, fisheries data.

*Ecological implications*

Loss of top predators; possible trophic cascade effects.



Parrotfish biomass (genus: Sparisoma: stoplight, redband, yellowtail, redband)

*What is the trend?*

### Decrease

*Possible main interpretation*

Overfishing (fishing down the food web) and/ or loss of habitat.

*Other variables to look at*

Macroalgal cover (preferably by species), turf algal cover and canopy height, rugosity.

*Ecological implications*

Loss of important macroalgal and turf grazers – increases in turf height and macroalgal cover/ height, loss of reef resilience.



Mesopredators biomass (hinds, graysbys, coneys, small snappers, trumpetfishes)

*What is the trend?*

### Increase

*Possible main interpretation*

Top trophic level (mostly large-bodied grouper) overfished – leading to an escape from predation

*Other variables to look at*

Abundance and size data for top predators (large groupers and snappers, barracuda), fisheries data.

*Ecological implications*

Possible trophic cascade effects – decrease in biomass of damselfish and other mesopredator prey items.



*What is the trend?*

### Decrease

(with no increase in top predators)

*Possible main interpretation*

Fishing through the food web (at all level simultaneously) – overfishing.

*Other variables to look at*

Abundance and size data for top predators (large groupers and snappers, barracuda), fisheries data.

*Ecological implications*

Loss of functional role of top predators; increase in damselfish abundance which may result in more algal growth.



Parrotfish biomass (genus Scarus: queen, striped, princess)

*What is the trend?*

### Decrease

*Possible main interpretation*

If only in smaller parrotfish species (e.g. *Scarus iseri*), possible increase in abundance of mesopredators or habitat loss.

*Other variables to look at*

Turf algal cover and canopy height, rugosity, mesopredator biomass.

*Ecological implications*

Loss of herbivores with highest grazing rate – increase in turf height, loss of reef resilience.



Conch density

*What is the trend?*

### Decrease

*Possible main interpretation*

Increase in fishing pressure (overfishing), loss of habitat.

*Other variables to look at*

Fisheries data.

*Ecological implications*

Loss of conch fisheries productivity, population may be unable to sustain itself if less than 47 individuals ha<sup>-1</sup>.



Lobster density

*What is the trend?*

### Decrease

*Possible main interpretation*

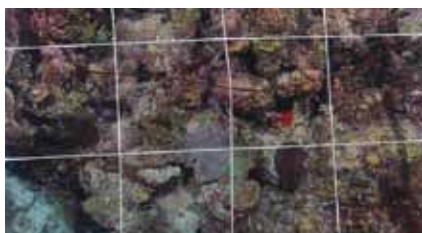
Increase in fishing pressure (overfishing), loss of habitat, disease outbreak.

*Other variables to look at*

Fisheries data, size classes (largest sizes removed by fishing).

*Ecological implications*

Loss of lobster fishery productivity, reduced spawning potential.



Coral cover

*What is the trend?*

### Acute decrease

*Possible main interpretation*

- Reef impacted by major disturbance causing high coral mortality, e.g. hurricanes, ship groundings, mass coral bleaching, disease outbreak, coral blasting.
- Look at coral cover by species to determine potential disturbance.

*Other variables to look at*

Coral cover by species, rugosity.

*Ecological implications*

Increase in other benthic organisms, potential decrease in substrate suitable for coral recruitment, loss of rugosity, sudden reduction in grazing intensity could allow algal bloom.



*What is the trend?*

### Chronic decrease

*Possible main interpretation*

- Continuous stressor on reef preventing adequate coral recruitment, causing coral mortality or both e.g. thick algal turfs, disease at low incidence.
- Look at coral cover by species to determine potential disturbance.

*Other variables to look at*

Coral recruitment, juvenile coral density, coral cover by species, rugosity.

*Ecological implications*

Chronic loss of resilience. Either insufficient recruitment or rates of background coral mortality have increased recently.



Density of juvenile corals

*What is the trend?*

### Decrease or low level

*Possible main interpretation*

Most likely because of a reduction in the quality of the settlement habitat, brought on by thicker algal turfs and/or macroalgae. Could also result from a decrease in the availability of larvae though this has rarely been demonstrated.

*Other variables to look at*

Recruitment onto settlement tiles. Coral cover by reproductive type (brooders/spawners), algal cover by functional group (CCA, turf, EAM, MA, bare), herbivore biomass (fish) and density (urchins).

*Ecological implications*

Losing supply of new individuals for population maintenance and recovery, loss of genetic diversity.



Coral bleaching

*What is the trend?*

### Presence

*Possible main interpretation*

- The expulsion of zooxanthellae (Symbiodinium) from corals due to external factors/stressors.
- Mostly likely caused by exceptionally high temperature or an exceptionally high level of sunlight (e.g., if calm conditions reduce the sediment load in a lagoon). At high latitudes, bleaching can also be associated with low temperature or salinity stress.
- Note: corals do not necessarily die after bleaching.

*Other variables to look at*

Coral cover by species, permanent quadrats to monitor individual colonies; oceanographic data, coral disease prevalence.

*Ecological implications*

Coral mortality (decrease in live coral cover), coral cover by species, reduce reproductive potential, decrease in net rates of calcium carbonate accretion and primary productivity, increase in other benthic organisms, loss of rugosity.



Coral cover by growth form or species

*What is the trend?*

### Decrease

*Possible main interpretation*

- Different growth forms (massive, branching, etc.) vary in their response to disturbance.
- Agaricids (e.g., leaf corals) are highly susceptible to both bleaching and overgrowth by macroalgae.
- *Acropora cervicornis* is easily fragmented by storms. *A. palmata* can become infested by *Drupella* especially if the coral is not that abundant.
- Large star corals (*Orbicella* spp.) bleach easily but tend to be relatively resistant to bleaching-induced mortality. However, these corals can be among the most susceptible to diseases, including those that follow bleaching. *Acropora* is usually the most resistant to bleaching.

*Other variables to look at*

Coral cover by species, rugosity

*Ecological implications*

Decrease in coral cover, increase in other benthic organisms, potential decrease in substrate suitable for coral recruitment, loss of rugosity.



Coral disease prevalence

*What is the trend?*

### Increase

*Possible main interpretation*

- Presence of bacteria/viruses and/or external stressors and/or favourable environmental conditions such as extreme temperatures, sedimentation, excess nutrients and toxins that cause disease. A commonly observed triggering factor is water temperature increase.
- To find out whether corals are dying, recovering or staying diseased, set permanent quadrats to monitor individual colonies.
- Different coral species are susceptible to different coral diseases. Injured colonies are most susceptible to infection when in contact with a diseased colony.

*Other variables to look at*

Tag colonies to obtain data on rates of disease incidence, recovery, and mortality; oceanographic data (temperature, nutrients), proximity to sources of nutrients.

*Ecological implications*

Coral mortality increase in other benthic organisms, disease transmission between colonies (further decrease in coral cover/increase disease prevalence).



Sponge cover

*What is the trend?*

### Increase

*Possible main interpretation*

Reef impacted by decreased water quality due to changes in land use, increased runoff or sewage input.

*Other variables to look at*

Coral cover, macroalgae cover, turf height, cover of other benthic heterotrophic feeders.

*Ecological implications*

Increase in bioerosion, competitive exclusion and decrease substrate available for recruitment of other benthic organisms.



Rubble cover

*What is the trend?*

### Acute increase

*Possible main interpretation*

Reef impacted by major mechanical disturbance (e.g. hurricanes, ship groundings) causing coral mortality and fragmentation in situ or in neighboring reefs. Ship groundings usually obvious and small in scale.

*Other variables to look at*

Coral cover, rugosity.

*Ecological implications*

Substrate instability and low recruit survival, likely increase in bioerosion.



Rugosity

*What is the trend?*

### Decrease

*Possible main interpretation*

Rapid declines expected after major storm or disease of *Acropora*. But if rapid decline in the absence of these impacts, it implies that bioerosion is extremely high (e.g. due to sponge bioerosion or overabundance of urchins).

*Other variables to look at*

Coral cover and community species composition.

*Ecological implications*

Increase in bioerosion, decrease in structural complexity, decrease in fish recruitment and overall abundance; reduced fisheries productivity.

Sea urchin (*Diadema*) density

*What is the trend?*

### Decrease

*Possible main interpretation*

Urchin disease outbreak and/or increase of predator populations.

*Other variables to look at*

Urchin disease prevalence, predator biomass.

*Ecological implications*

Increase in macroalgal cover. Functionally non-existent below 1 m<sup>-2</sup>.

*What is the trend?*

### Increase

*Possible main interpretation*

Increase in recruitment and/or reduction of predator populations.

*Other variables to look at*

Urchin recruitment, predator biomass.

*Ecological implications*

Decrease in macroalgal cover, increase in bioerosion. Potential overabundance when density greater than approx. 5 m<sup>-2</sup>.



Cover of sand and bare rock

*What is the trend?*

### Increase

*Possible main interpretation*

- Reef impacted by storm which redistributed sand on the reef or exposed bare rock.
- Reef impacted by major mechanical disturbance (e.g. hurricanes, ship groundings, coral blasting) causing coral fragmentation and disintegration and the formation of new sand.

*Other variables to look at*

Coral cover, rugosity, abundance of bioeroders.

*Ecological implications*

- If increases in sand: possible increase in bioerosion, decrease of substrate available for recruitment.
- If increases in bare rock: increase of substrate available for recruitment.



Cover of other living (e.g. Corallimorphs, Zoanthids)

*What is the trend?*

### Increase

*Possible main interpretation*

Reef possibly impacted by decreased water quality due to changes in land use, increased runoff or sewage input.

*Other variables to look at*

Coral cover, macroalgal cover, turf height, cover of other benthic heterotrophic feeders.

*Ecological implications*

Increase in bioerosion, competitive exclusion and decreased substrate available for recruitment of other benthic organisms.



Octocoral density

*What is the trend?*

### Decrease

*Possible main interpretation*

Octocoral disease outbreak; might link to terrestrial runoff.

*Other variables to look at*

- Octocoral disease prevalence.
- Macroalgal cover, turf height, cover of benthic heterotrophic feeders.

*Ecological implications*

Decrease in structural complexity.



CCA cover

*What is the trend?*

### Decrease

*Possible main interpretation*

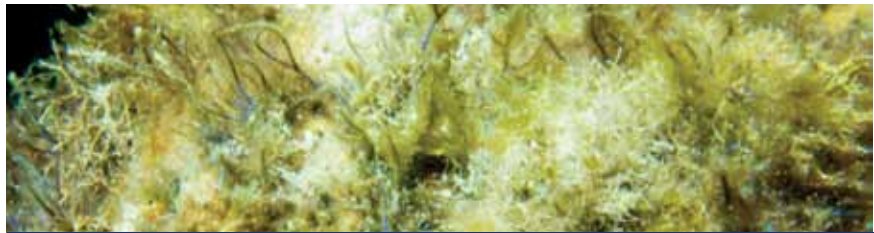
- Increase in thick algal turfs, particularly if sediments present.
- Possible diseases of CCAs.

*Other variables to look at*

- Algal turf canopy height.
- Survey of disease prevalence.
- Sedimentation.

*Ecological implications*

- Decrease in carbonate production, reef accretion and stability. Increase in reef erosion.
- Reduce settlement cues for coral larvae.
- Reduce overall reef resilience.



Turf cover

*What is the trend?*

### Acute increase

*Possible main interpretation*

- Increase in substrate availability due to coral mortality from acute disturbance.
- Sudden increase in nutrient inputs after storms. Not necessarily a problem.

*Other variables to look at*

- Coral cover
- Algal canopy height

*Ecological implications*

Only likely to be a problem if accompanied by an increase in turf canopy height.

*What is the trend?*

### Chronic increase

*Possible main interpretation*

- Overfishing of herbivores and/or the predators of urchins.
- Increase in nutrient availability and pollutants (e.g. from terrestrial runoff).
- Changes in environmental conditions (e.g. rainfall, river flow, light, water temp).
- Could indicate an increase in the abundance of garden-forming damselfish.

*Other variables to look at*

- Herbivore biomass, density.
- Water quality (nutrients, turbidity).
- Trends in damselfish density.

*Ecological implications*

- Only likely to be a problem if accompanied by an increase in turf canopy height.

Macroalgal cover  
by growth form and species

*What is the trend?*

### Increase

*Possible main interpretation*

- Lots of important variability. Some of the most common fleshy macroalgae on reefs suggest the following insights:
- *Lobophora* – tends to have limited seasonality and not strongly influenced by wave exposure. But one of the most problematic algae for other organisms such as coral and sponges (i.e., very strong competitor).
- *Dicyota* spp. – Can have very erratic dynamics including summer blooms. Note that blooms can change under upwelling conditions. Difficult to interpret a change in this group unless it persists over time.
- *Halimeda* spp – An increase in microhabitats that are usually intensively grazed, such as the tops of (dead) coral heads, suggests that grazing is chronically low.

*Other variables to look at*

Shift in algal species composition.



Macroalgal cover (and/or volume)

*What is the trend?*

### Acute increase

*Possible main interpretation*

- Increase in substrate availability due to coral mortality after reef is impacted by physical disturbance (e.g. tropical storms).
- Sudden increase in nutrients due to increased runoff or sewage input.
- Possible seasonal variation if historical data in that season not available to confirm natural patterns. For example, *Dictyota* blooms in summer in many places. Reefs associated with large banks – e.g., Bahamas, Turks and Caicos – tend to have natural seasonal blooms of *Microdictyon* in summer.
- Disease of *Diadema*.

*Other variables to look at*

- Changes in coral cover
- Algal species composition
- Water quality (nutrients and sediment loading).
- Herbivore density and biomass.

*Ecological implications*

- Overgrowth of corals. If herbivory is low, a phase shift to macroalgal-dominated reefs and decrease in carbonate production.
- Changes in species composition, competitive exclusion, losses or shifts in diversity and ecological roles

*What is the trend?*

### Chronic increase

*Possible main interpretation*

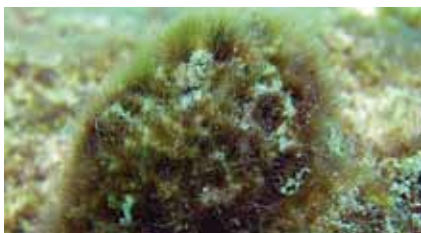
- Overfishing of herbivores.
- Changes in environmental conditions (e.g. regional rainfall, river flow) leading to increase of nutrient inputs and a reduction in water clarity.

*Other variables to look at*

- Water quality (e.g. nutrients, sediment loading, turbidity).
- Changes in fish size structure, fish biomass or fishing pressure data.
- Changes in coral cover,
- Shift in algal species composition.

*Ecological implications*

- Reduction in coral recruitment and recovery.
- If herbivory is low, a phase shift to macroalgal-dominated reefs and decrease in carbonate production.
- Loss in diversity and decrease in structural complexity.



Turf canopy height

*What is the trend?*

### **Increase**

*Possible main interpretation*

Reduction in grazing intensity that can occur for several complementary reasons:

- Rapid increase in dead coral (substrate available for herbivore feeding).
- Decrease in herbivore size, biomass, density.
- Increased nutrient supply
- Increase in density of damselfish that defend algal gardens (e.g., *Stegastes planifrons*).

*Other variables to look at*

- Herbivore biomass
- *Diadema* density
- Water quality
- Coral cover
- Damselfish density

*Ecological implications*

- Indicator of a possible shift towards increased macroalgae and likely to result in reduced coral recruitment.
- Healthy system 2mm or less. Greater or equal than 5mm shutdown in coral recruitment.



Cyanobacteria cover

*What is the trend?*

### **Increase**

*Possible main interpretation*

- Terrestrial inputs
- Nutrient increase

*Other variables to look at*

Shift in algal species composition.

*Ecological implications*

Changes in chemical microhabitats for coral recruitment.

## Reef monitoring - supporting references

### Fish

Appeldoorn et al. 2011; Arnold et al. 2010; Behringer et al. 2009; Bozec et al. 2013; Burke 1995; Burkepile & Hay 2008; Ehrhardt et al. 2011; Ferrari et al. 2012; Graham et al. 2005; Graham & Nash 2012; Green et al. 2012; Harborne et al. 2009; Micheli et al. 2014; Morris & Akins 2009; Mumby et al. 2005; Mumby 2006; Mumby, Hastings, et al. 2007; Mumby et al. 2012; Rogers et al. 2014; Stoner et al. 2012; Williams & Polunin 2001; Wynne & Côté 2007

### Coral

Arnold et al. 2010; Brown 1997a; Brown 1997b; Done 1999; Douglas 2003; Eakin et al. 2010; Glynn 1996; Harvell et al. 2007; Hoegh-Guldberg 1999; Jones et al. 2009; McCook et al. 2001; Muller et al. 2008; Mumby, Harborne, et al. 2007; Peters 1997; Randall & Szmant 2009; Rogers 1990; Scoffin 1993; Smith & Buddemeier 1992; Szmant & Gassman 1990; Vega Thurber et al. 2014; Weil et al. 2006; Wilkinson 1999; Williams & Bunkley-Williams 1990

### Other Benthic

Alvarez-Filip, Côté, et al. 2011; Alvarez-Filip, Dulvy, et al. 2011; Carpenter 1984; Carpenter & Edmunds 2006; Cooper et al. 2008; Cooper et al. 2009; Fabricius 2005; Glynn 1997; Harvell et al. 2007; Hernandez-Munoz et al. 2008; Kuguru et al. 2004; Lapointe et al. 2010; Lessios 1988; Lessios et al. 1984; López-Victoria et al. 2006; Mah & Stearn 1986; Rasser & Riegl 2002; Ward-Paige et al. 2005; Webster 2007

### Algae

Arnold et al. 2010; Arnold & Steneck 2011; Davies et al. 2014; Diaz-Pulido 2002; Diaz-Pulido et al. 2012; Diaz-Pulido & McCook 2004; Kuffner et al. 2006; Kuffner et al. 2008; Mumby et al. 2005; Paul et al. 2005; Renken 2008; Renken et al. 2010; Vermeij et al. 2010; Webster et al. 2010





Peter Mumby

University of Exeter /University of Queensland



#### OUR RESEARCH

Our research focuses on delivering science to improve the management of coral reefs. We carry out empirical ecological studies at scales ranging from millimetres (algal patch dynamics) to thousands of kilometres (gene flow in Caribbean corals) in an effort to plug gaps in our understanding of reef processes. Empirical data are then used to develop ecosystem models from which we can investigate the effectiveness of conservation measures in mitigating disturbance on reefs including climate change.

*When I started working on coral reef management in 1992, there was not much science available to guide decision-making. But while scientists always talk about the need to know more – which is their job after all – there is now a wealth of information from which to base and justify decisions.*

*Natural science justifies the need to control pollution, control fishing, and reduce local damage to reefs. Social sciences tells us the principles of good governance. Yet, despite progressive action on management throughout the region, each step forward seems to be met with one step back, particularly in meeting the challenge of development, be it cruise ship terminals or land clearance for housing.*

*To me, turning of the tide will require renewed commitment of the public to see a change of beneficiaries. All too often the beneficiaries are large international companies and local people experience the cost of a degraded and dwindling environment. Science can play a role here in trying to illuminate the real costs and benefits of development, making it transparent for all to see. This goes beyond hard economics and considers the ways in which peoples' quality of life is influenced by a clean, healthy, and safe environment. But having the science is only part of the answer; we need a governance framework that allows common stakeholders and public to influence the decision-making process. And it is here that government and managers can make a start.*

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# GLOSSARY

## **accretion**

The process of growth or enlargement either by a) organic growth: continued development from within, or b) increase by external addition or accumulation

## **acidification**

The process by which acids are added to a water body, leading to a significant decrease in pH that may lead to the water body becoming acidic. This is a common form of water pollution.

## **anthropogenic**

Applied to substances, processes, etc. of human origin, or that result from human activity.

## **aragonite**

A colourless mineral, the stable form of calcium carbonate. It is different from calcite, the more common form of calcium carbonate, by its greater hardness. Aragonite is the mineral normally found in pearls and mollusc shells are formed of aragonite crystals.

## **assemblage**

A group of plants and/or animals that is indicative of a particular environment.

## **benthic algae**

Algae that live attached to the sea bottom.

## **benthic communities**

Life attached, moving or occurring at the base of bodies of water.

## **bioerosion**

Erosion or decay caused by living organisms such as mollusks, sponges, crustaceans, either by boring, drilling, rasping, or scraping.

## **bioindicator**

An organism used as an indicator of the quality of an ecosystem, especially in terms of pollution.

## **biomass**

The total quantity or weight of organisms in a given area or volume.

## **broadcast spawner**

Coral that releases eggs and sperm directly into the sea for external fertilization.

## **brooder**

Coral that harbours or broods developing larvae within its polyps.

## **calcium carbonate**

A white solid chemical compound that is found as chalk, limestone, or marble, and in animal shells and bone.

## **calcification**

The process by which corals and calcareous algae extract calcium from seawater and produce it as calcium carbonate to form skeletons in corals and the shells of molluscs.

## **carbon**

Extracted from carbon dioxide by plants during photosynthesis, is incorporated in living matter, and when organic matter decomposes its carbon is combined chemically with oxygen and returned to the atmosphere as carbon dioxide.

## **carbon budget**

A record or estimation of carbon in an area or system, and the flux into and out of this system.

## **carbon cycle**

One of the major cycles of chemical elements in the environment. Carbon (as carbon dioxide) is taken up from the atmosphere and incorporated into the tissues of plants in photosynthesis. It may then pass into the bodies of animals as the plants are eaten (food chain). During the respiration of plants, animals, and organisms that cause decomposition, carbon dioxide is returned to the atmosphere. The combustion of fossil fuels (e.g. coal) also releases carbon dioxide into the atmosphere.

## **coralline algae**

A branching pink/reddish seaweed with a calcium carbonate jointed stem.

## **corallivory**

The act of eating coral polyps by some marine organisms.

## **Cost–Benefit Analysis (CBA)**

A primary tool that economists use to determine whether a particular policy promotes economic efficiency. CBA is an aggregator of all impacts, to all affected parties, at all points in time. The impacts, both positive and negative, are converted into a common monetary unit, and the cost–benefit measure is simply a test of whether the benefits exceed the costs.

## **crustose coralline algae**

Red algae that cement and bind the reef together. Crustose corallines resemble pink or purple pavement. They can range from smooth and flat, to rough and knobby, or even leafy

## **cyanobacteria**

Often called blue-green algae, these photosynthetic aquatic bacteria have no relationship to algae.

## **marine dissolved organic matter**

Marine dissolved organic matter is a complex mixture of molecules of diverse origins found in seawater. It affects the penetration of light, the exchange of gases at the sea surface and the availability of trace metals and other nutrients to the community. Phytoplankton, including photosynthetic algae and bacteria, are the primary source of marine dissolved organic matter.

## **eutrophication**

Excessive richness of nutrients in a lake or other body of water, frequently due to runoff from the land, which causes a dense growth of plant life limiting the oxygen needed for animal life.

## **excavating sponges**

Also called boring sponges, marine sponge which bores passages in mollusks, shells, corals, limestone, and other calcium carbonate matter.

## **fix**

Biology (Of a plant or microorganism) absorb (nitrogen or carbon dioxide) by forming a non-gaseous compound.

## **fragmentation**

A method of asexual reproduction, occurring in some invertebrate animals, in which parts of the organism break off and develop into new individuals.

## **food web**

A series of interconnected and overlapping food chains in an ecosystem.

## **fore reef**

A talus or straight slope on the seaward side of a reef, constantly under attack by waves and currents.

## **gamete**

Reproductive sex cell that joins with another sex cell to form a new organism. Female gametes (ova) are usually motionless; male gametes (sperm) often have a tail (flagellum).

## **hedonic pricing**

A technique used to investigate how environmental quality affects the prices of other goods and services. It is widely used to explain variations in house prices in terms of variations in environmental quality (such as air pollution, water pollution, or noise) and environmental amenities (such as attractive views or access to recreational sites).

## **herbivore**

An animal that feeds on plants.

## **hermatypic corals**

Refers to 'stony corals' which are reef-building corals.

## **Institutions**

Institutions can be thought of as the 'rules of the game' in any society, and the formal or informal structures, mechanisms and processes that establish those rules.

## **macroalgae**

Another name for seaweed.

## **matrices**

A rectangular array of quantities or expressions in rows and columns that is treated as a single entity and manipulated according to particular rules.

**mesopredator**

A medium-sized predator which often increases in abundance when larger predators are eliminated.

**metapopulation**

A set of partially isolated populations that belong to the same species, between which individuals can freely migrate.

**microbial degradation**

Processes of decomposition and breakdown of materials by the action of micro-organisms, principally bacteria and fungi.

**microsatellites**

Regions within DNA sequences where short sequences are repeated one right after the other. They are widely used in the population studies and conservation biology to detect sudden changes in population, effects of population fragmentation, and interaction of different populations.

**mitochondrial DNA**

DNA that is found in mitochondria in most cells, in which the biochemical processes of respiration and energy production occur. It is entirely independent of nuclear DNA and, with very few exceptions, is transmitted from females to their offspring.

**multi-criteria analysis (MCA)**

In a MCA, you quantify your criteria in different units or qualitative terms, using a ranking or rating format. By determining the relative importance of the criteria it is possible to compare different alternatives based on these criteria.

**multiple driver effects**

Drivers are factors which bring about a situation that is observed to exist or happen. Such factors include fishing, sedimentation, grazing, predation and recruitment; the effects are the changes which are a result or consequence of those factors.

**nitrogen**

A colourless, tasteless, odourless gas, that exists in the atmosphere or as a dissolved gas in water; is a nutrient for plants. It is produced in septic systems, animal feed lots, agricultural fertilizers, industrial wastewaters and garbage dumps.

**pathogen**

An organism (bacterium, virus or other microorganisms) which causes a disease within another organism.

**phosphorus**

An element essential for the growth of organisms Phosphorus is also released into the environment by fertilizers and detergents where they act as a nutrient pollutant in water.

**physicochemical**

Relating to physics and chemistry or to physical chemistry.

**phytoplankton**

Microscopic plant-like organisms that live in the ocean and are the foundation of the marine food chain.

**photosynthetic**

Green plants that go through the process of photosynthesis which is the combining of carbon dioxide and water, by using energy from light, to produce their own food.

**plankton**

Plankton is made up of animals and plants that either float passively in the water, or with limited powers of swimming are carried from place to place by the currents.

**polyp**

A small tube-like marine animal which lives in warm, clear seas and grows attached to the sea-bed, to rocks, or to other polyps. On the other end is a mouth surrounded by finger-like, stinging tentacles. Live coral is made of polyps.

**proximate drivers**

Causes of reef decline that include coral bleaching, ocean acidification, hurricane damage, algal blooms, coral disease, sedimentation, invasive species and disease of sea urchin, *Diadema antillarum*.

**proxy**

Substitute or surrogate.

**recruitment**

The addition of new members into a population by reproduction or immigration.

**saturation states**

Surface tropical seawaters are generally supersaturated with respect to the carbonate minerals (e.g. calcite, aragonite) from which marine organisms construct their shells and frameworks. We refer to the degree to which seawater is saturated with respect to these minerals as 'saturation state'.

**senescence**

The condition or process of deterioration with age.

**sessile**

(Of an organism, e.g. a barnacle) fixed in one place; immobile.

**sink**

A body or process which acts to absorb or remove energy or a particular component from a system.

**spatiotemporal**

Of, relating to, or existing in both space and time.

**substrate**

The surface or material on or from which an organism lives, grows, or obtains its nourishment.

**symbiont**

An organism living in a mutually beneficial relationship with another organism from a different species.

**symbiosis**

Association of two different organisms (usually two plants, or an animal and a plant) which live attached to each other, or one as a tenant of the other, and contribute to each other's support.

**Total economic value (TEV)**

The overall economic value of a particular natural resource, taking into account both use and non-use values. The sum of these ecosystem services is defined as the TEV of that ecosystem and is normally expressed as a yearly value.

**trophic**

Of or pertaining to the feeding habits of, and the food relationship between, different types of organisms in the food-cycle.

**trophic cascade**

An ecological phenomenon triggered by the addition or removal of top predators changes the relative populations of predator and prey through a food chain, which often results in dramatic changes in ecosystem structure and nutrient cycling.

**trophic transfer**

Energy or nutritional transfer within a food web.

**trophic structure**

The organisation of the links within an ecosystem based on communities of organisms (species) and their feeding habits.

**turf algae**

densely packed algae with thread-like strands which rise less than one centimeter above the substratum where they are growing.

**ultimate drivers**

Causes of reef decline that include rising atmospheric carbon dioxide, rising sea temperature, overpopulation, poor governance, inappropriate coastal development, destructive fishing practices, overfishing, agricultural fertilisers and pesticides, elevated watersheds, inadequate environmental education.

**zooxanthellae**

Photosynthetic algae that live in the tissues of most reef-building corals. They have a mutualistic relationship with coral. The coral provides the algae with a protected environment and compounds they need for photosynthesis. In return, the algae produce oxygen and help the coral to remove wastes.



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## Authors

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Keep Our Islands Green



and Our Reefs Clean

*This handbook aims to provide reef managers with tools, information and recommendations on management of coral reef ecosystems.*

*The handbook sections range from ecological history and biogeography, resilience as well as climate change issues to fisheries, governance and the monitoring of coral reef ecosystems. Within each section are practical stand-alone 'briefs'. These briefs offer concise information on particular reef-related issues, utilising some of the most recent scientific research to inform management actions. Each of the briefings are a unique grab-and-go resource.*

*The accessible format also provides a useful resource for students, researchers, policy-makers and anyone interested in the future of Caribbean coral reefs.*



The Future of Reefs in a Changing Environment (FORCE) project partners a multi-disciplinary team of researchers from the Caribbean, Europe, USA and Australia to enhance the scientific basis for managing coral reefs in an era of rapid climate change and unprecedented human pressure on coastal and coral reef resources.

[www.force-project.eu](http://www.force-project.eu)



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