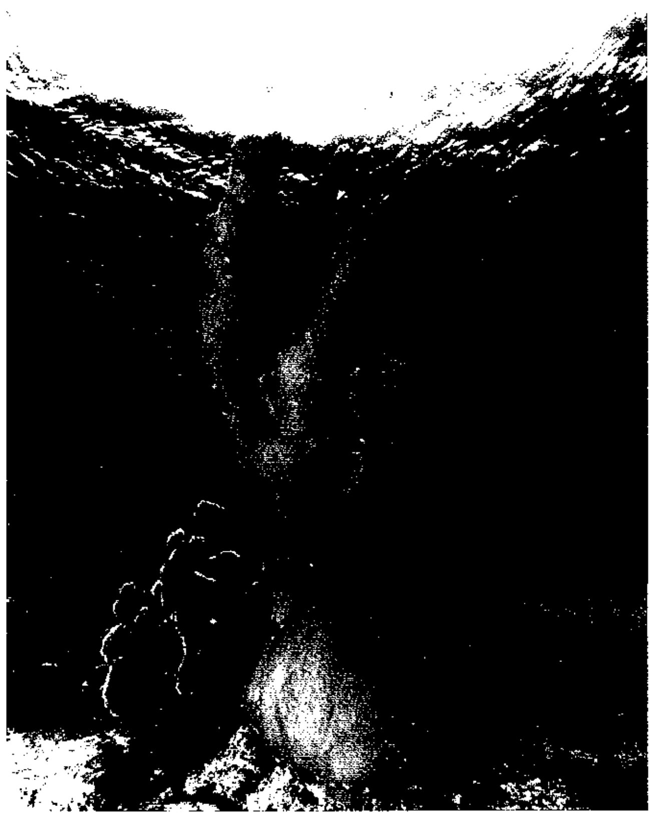
ENCOUNTER

Magazine of the International Society for Reef Studies



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Magazine of the International Society for Reef Studies

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The **International Society for Reef Studies** was founded at a meeting in Churchill College, Cambridge, UK in December 1980.

Its aim under the constitution is to promote for the benefit of the public, the production and dissemination of scientific knowledge and understanding concerning coral reefs, both living and fossil.

In order to achieve its aim, the Society has the following powers:

i. To hold meetings, symposia, conferences and other gatherings to disseminate this scientific knowledge and understanding of coral reefs, both living and fossil.

ii. To print, publish and sell, lend and distribute any papers, treatise or communications relating to coral reefs, living and fossil, and any Reports of the Proceedings or the Accounts of the Society

iii. To raise funds and invite and receive contributions from any persons whatsoever by way of subscription, donation or otherwise providing that the Society shall not undertake any permanent trading activities in raising funds for its primary objects.

The Society collaborates with Springer-Verlag in producing the quarterly journal Coral Reefs. This large-format journal is issued free of charge to all members of the Society, and concentrates on quantitative and theoretical reef studies, including experimental and laboratory work and modelling.

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Cover image: This photo of *Acropora palmata* was taken in Bonaire in 2005 by Marlon Pereira (www.bluesubmersion.com)

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EDITORIAL

Welcome to the special edition of **Reef Encounter,** where we are pleased to present the 2005 **ISRS** briefing papers. The aim of the briefing papers is to present information to an extensive audience regarding the future of coral reefs and the societies that depend on them. Specifically, these briefing papers examine the role of marine protected areas, water quality issues, and sustainable fisheries management. The briefing paper focusing on marine protected areas (MPAs) examines the use and potential of MPAs for coral reef management and conservation. The water quality briefing paper addresses the impacts of degraded water quality from increases in terrestrial run-off and other pollutants on the coral reef environment and reef products. This is important because hundreds of countries around the world utilize coral reefs for both cultural and economic resources. An additional briefing paper focuses on the demand for sustainable reef fisheries and the significance of maintaining a balance between production and consumption. Recommendations are offered at the end of each briefing paper in order to provide reassurance and potential opportunities to countries that rely on coral reefs for their economic and aesthetic values.

Also included in this special edition is a statement that was released by the **ISRS** in 2005 regarding coral disease. The detrimental effects of coral disease are particularly evident on the reefs of the Caribbean, and scientists are eager to discover more about the causes and transmission of several diseases that are currently observed on reefs today.

We would like to express our appreciation for the tireless work of the authors of the briefing papers. Reef Encounter welcomes all articles or announcements that may be of interest to the **ISRS** community. We look forward to hearing from you!

WF Precht, B Zimmer and ML Robbart

ISRS NEWS

President's Message

Since the 10th International Coral Reef Symposium in Okinawa, Japan in 2004, coral reef research and the sense of crisis surrounding the future of this ecosystem has continued to grow. In desperation, some scientists, environmentalists and environmental non-governmental organizations (NGOs) are resorting to emotive arguments that will attract the attention of decision-makers. However, there are many scientists proceeding with high-quality research programs which are based on empirical data. There are signs that some international and governmental agencies as well as NGO's have become more amenable to funding science. Despite this funding availability, much of the information produced will not reach the public domain, including the research in developing countries. One area of concern is that organizations have difficulty obtaining accurate and accessible information about issues such as benefits of marine protected areas, sustainability of fishing and consequences of land runoff for reefs. In order to provide accessible, unbiased information to the public, ISRS launched three briefing papers, one on each of the subjects listed above. While many of you may already be aware of these briefings, the ISRS Council feels it was important that members have their own copies of the briefings so they may further understand the Society's scientific outreach initiative.

On behalf of the ISRS, I strongly hope that these briefing papers are not the last. In the near future I hope to see additional briefing papers on subjects such as the effects of coral bleaching on ecosystem functions, physical protection provided by reefs such as protection from tsunamis and tourism values of coral reefs. If you have comments on the present briefing papers, or ideas for future topics, please communicate them to our Corresponding Secretary, Pete Mumby, at p.j.mumby@exeter.ac.uk

All the best to all our members!

Nicholas Polunin

ISRS President 2003–06

'CORAL REEFS' – Changes in the Editorial Team and a New Manuscript System.

On 1 July 2005, Barbara Brown took over the reins of Editor in Chief at **'Coral Reefs'** from Dick Dodge. Barbara has been closely associated with the journal, both at the time it was founded in 1982, and later from 1993 to 1998 when she served as a Topic Editor. The Editorial Office has moved to:

Coral Reefs Editorial Office, West Briscoe, Baldersdale, Barnard Castle, Co. Durham, DL12 9UP, UK. Tel +44 (0)1833 650059.

e-mail - CoralReefJournal@aol.com.

There have also been major changes at our publisher, Springer, where we have a new editorial team based in Holland following the merger between Springer and Kluwer Academic Publishing. The new company is the second largest professional publisher in the fields of science, technology and medicine worldwide.

ELECTRONIC MANUSCRIPT SUBMISSION

'Coral Reefs' has now introduced 'online' electronic manuscript processing. Authors can submit their manuscripts by logging on to the website: http://mc.manuscriptcentral.com/coral.

Electronic processing will help reduce delays in the review process, and allow closer control by the Editorial team to ensure a smooth flow of manuscripts from submission to publication. Authors will also be able to track their manuscripts through the various stages, and will be informed by e-mail as soon as a decision has been made. The existing 'online' electronic publishing in advance of the release of the printed journal also ensures that papers reach the press at an early stage.

For full details please visit the **'Coral Reefs'** web page where updated instructions can be found:

http://www.springeronline.com/sgw/cda/frontpage/0,11855,3-10034-70-1047854-0,00.html.

OTHER CHANGES AT THE JOURNAL

'Coral Reefs' is increasing its pages over the next few years. In the current year, the journal has a page allowance of 704 pages, in 2006 this rises to 800 and for 2007 and thereafter 900. The page increases will be used to reduce the period from acceptance to publication.

As well as full length papers, **'Coral Reefs'** publishes short manuscripts, or 'Notes,' which are valuable contributions to the science. To enhance their status, Notes will be allowed short abstracts in future. This will enable them to be cross referenced by the various abstracting services, and so improve their visibility to the research community.

JOURNAL RANKING

In the last year of assessment (2003), **'Coral Reefs'** was ranked 10th in the 'Marine and Freshwater Biology' publishing category by citation impact factor. This is an excellent achievement, and one on which the Editorial team wish to build.

The Editorial team are committed to these improvements to your journal. Our commitment is to grow **'Coral Reefs'** as a leading international journal, publishing high quality science, together with an improved service to authors.

BRIEFING PAPERS

Marine Protected Areas (MPAs) in Management of Coral Reefs[1]

Synopsis

Marine protected areas (MPAs) may stop all extractive uses, protect particular species or locally prohibit specific kinds of fishing. These areas may be established for reasons of conservation, tourism or fisheries management. This briefing paper discusses the potential uses of MPAs, factors that have affected their success and the conditions under which they are likely to be effective.

- MPAs are often established as a conservation tool, allowing protection of species sensitive to fishing and thus preserving intact ecosystems, their processes and biodiversity and ultimately their resilience to perturbations.
- Increases in charismatic species such as large groupers in MPAs combined with the perception that the reefs there are relatively pristine mean that MPAs can play a significant role in tourism.
- By reducing fishing mortality, effective MPAs have positive effects locally on abundances, biomass, sizes and reproductive outputs of many exploitable site-attached reef species.
- Because high biomass of focal species is sought but this is quickly depleted and is slow to recover, poaching is a problem in most reef MPAs.
- Target-species 'spillover' into fishing areas is likely occurring close to the MPA boundaries and benefits will often be related to MPA size. Evidence for MPAs acting as a source of larval export remains weak.
- The science of MPAs is at an early stage of its development and MPAs will rarely suffice alone to address the main objectives of fisheries management; concomitant control of effort and other measures are needed to reduce fishery impacts, sustain yields or help stocks to recover.
- The design and enforcement of MPAs often differs between wealthy and poorer nations, in the latter people often being much more dependent on resource exploitation.
- In most situations community involvement and support during MPA establishment are essential to MPA success.
- The design of MPAs must increasingly be adapted to the specific purpose or purposes set for reef management and this will be feasible with more improved scientific understanding of the recovery processes, their implications for fisheries and broader conservation, including the social and economic values.

[1] Cite as 'ISRS (2004) Marine Protected Areas (MPAs) in Management of Coral Reefs. Briefing Paper 1, International Society for Reef Studies, pp: 13'

Introduction

The establishment of marine protected areas (MPAs) on coral reefs has increasingly been considered a useful option for management of these systems (Clark et al. 1989, Jennings 2001). The general idea of MPAs is to locally stop all extractive uses, however some may protect only particular species or locally prohibit specific kinds of fishing (Bohnsack 1996). In this paper we are primarily referring to fully protected areas, often referred to as no-take marine reserves. The motivations for establishing these protected areas vary, but high on the list are economic benefits of tourism, maintenance of fisheries, conservation of coral reef ecosystems, and protection of traditional use (Clark et al. 1989). The use of MPAs as a traditional management technique in regions such as Southeast Asia and the Pacific dates back centuries in some cases (Johannes 1998) and despite increased external pressures, their use are increasing in many areas (Johannes 2002). Although the objectives of MPAs may work in synergy, MPAs are often established with certain goals, for example increased tourism revenue, in mind. This has wide connotations for the design of the areas, including placement, optimum size, habitats and enforcement (Roberts et al. 2003). Compliance with the rules of MPA management is widely a problem (Russ 2002) and in the majority of cases, the support and involvement of local fishing communities in particular is considered to be essential (Francis et al. 2002).

This briefing paper addresses the uses and issues surrounding the application of MPAs in the management of coral reefs. The paper first assesses the issues that MPAs might address on reefs and how these conflict or complement each other. The factors which have affected the success of MPAs are then reviewed, covering issues such as mobility of fish, enforcement, economic development and ecological control of the ecosystem. The paper concludes by discussing conditions under which MPAs are likely to be effective.

Issues Addressed by MPAs

Conservation

An important function of MPAs is that they protect species that are very sensitive to fishing. For example, MPAs can protect fragile benthic habitat-forming organisms, such as gorgonians, from the direct physical impacts of fishing (Polunin 2002) and thus generally improve habitat quality within the area protected (Rodwell et al. 2003).

Improved habitat quality may enhance overall reef biodiversity. They will also protect slow growing species of fish and invertebrates that are particularly susceptible to overfishing due to their life history characteristics. Indeed, MPAs serve to protect the full diversity of species and maintain species that would not do well under any sort of fisheries management system. With build up of piscivorous target species within MPAs, reduction in abundance of some prey species is expected (Graham et al. 2003), but patterns can be expected to be complex and take 20 or more years to reach equilibrium (Pinnegar & Polunin 2004). Build up of herbivorous grazers within MPAs may be expected to control macro-algal overgrowth and increase ecosystem resilience in the face of perturbations such as hurricanes, crown-of-thorns starfish outbreaks and mass bleaching events that often result in 'phase shifts' on reefs (Williams et al. 2001; Hughes et al. 2003; West & Salm 2003). Due to such large-scale impacts on reefs, reducing at least some anthropogenic stressors, is reason enough for MPA establishment in some locations. Given these benefits from MPAs, a primary focus of many established areas, particularly nationally established protected areas, is to preserve intact ecosystems, their processes and biodiversity. In doing so, they also provide useful controls for scientific study into understanding the human effects on these ecosystems.

Tourism

Many MPAs are established to attract tourists and the economic benefits of this may far outweigh those gained from fishing (Polunin 2002). Increases in abundance, size and diversity of reef-associated fishes in reef MPAs can be more valued by divers than the condition of the reef itself (Williams & Polunin 2000). Many dive operators in the Caribbean conduct most of their diving within MPAs (Green & Donnelly 2003). Only 25% of the MPAs charge an entry fee, generating annual revenue of approximately US$1–2million, and this might be greatly enhanced (Green & Donnelly 2003). In the Seychelles very few tourists express an unwillingness to pay entrance fees, and the majority are willing to pay a fee of US$12 (Mathieu et al. 2003). In most situations this revenue will scarcely reach the local communities involved (Polunin 2002), however if this were changed, MPAs should help alleviate fishing pressure in surrounding areas through compensation or providing alternative sources of income.

Fisheries

There are seven main benefits hoped to be derived from an MPA for fisheries, five within the MPA (lower fishing mortality, higher density of target species, higher mean size and age of target species, higher biomass of target species and higher production of propagules of target species) and two outside the MPA (export of adult fishes to fished areas [spillover] and export of eggs and larvae to fished areas [recruitment effect]) (Russ 2002). It is therefore hoped that MPAs will promote recovery of stocks and ecosystem functioning within the area and provide for sustainable yield through spillover and larval export outside of it. Although these expectations are

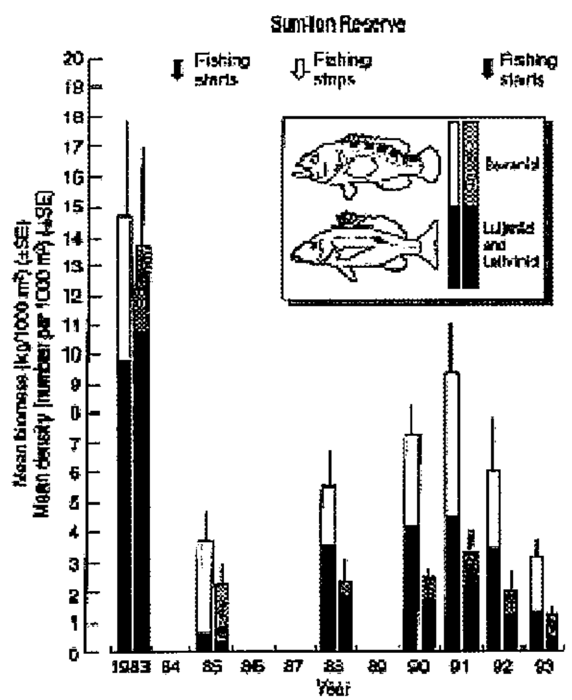

Figure 1. Mean number (left columns) and mean biomass (right columns) of large predatory reef fish per 1000 m2 in the Sumilon MPA, Philippines, from 1983–1993. From Russ & Alcala 1999.

widely discussed (e.g. Roberts & Polunin 1991; Bohnsack 1996; Roberts 1998; Polunin 2002; Russ 2002; Gell & Roberts 2003; Halpern 2003), at this time there are relatively few good empirical studies of the actual functioning of MPAs, and these studies are often poorly designed (Russ 2002; Willis et al. 2003).

Reducing or eliminating fishing mortality in MPAs is the most important aim if the other objectives are to be achieved. The biomass of target species may take a long time to build up to unexploited levels within MPAs, yet it can be fished down very rapidly (Fig. 1) (Russ & Alcala 1999) and this is an argument against rotational closure in the absence of other controls on effort. Despite this, there have been few measurements of fishing mortality in relation to MPA function and affective enforcement appears to be the exception rather than the rule, even for well developed MPA systems in more developed countries (Russ 2002). Increases in density, biomass and mean body size of site-attached target species have been documented from MPAs in many regions of the world including East Africa (McClanahan & Shafir 1990; McClanahan 1994; Watson & Ormond 1994), the Red Sea (Galal et al. 2002), Florida (Clark et al. 1989), the Caribbean (Koslow et al. 1988; Polunin & Roberts 1993; Roberts 1995; Roberts et al. 2001), the Seychelles (Jennings et al. 1995, 1996), Hawaii (Friedlander et al. 2003), the Philippines (Russ & Alcala 1996a, 1999, 2004) and the Great Barrier Reef (Craik 1981; Evans & Russ in press). Early increases may be rapid (Halpern & Warner 2002), however full recovery can take decades for most fishery target species, which have 'slow' life history characteristics (Russ & Alcala 2004). These studies showing such effects within MPAs are relatively few however, and the majority are comparisons at one point in time and often only one site whereas before/after evidence with replicated sites are needed (Russ 2002). The strongest biomass effects are recorded when species data are aggregated in to taxanomic (e.g. family) or other groupings. Species-level data may not show an MPA effect, because of variability inherent in both the populations and the measurements. Empirical evidence for a higher production of propagules is nearly non-existent (Russ 2002). Tropical invertebrates may show increasing reproductive output (Dugan & Davis 1993), however the evidence for coral reef fish is mainly based on theoretical predictions from increases in fish density and size (Russ 2002).

Evidence in support of the spillover and recruitment effects outside of effective MPAs is very sparse. Movement of juvenile and adult fish occurs across the boundaries of effective MPAs (Alcala & Russ 1990; Russ & Alcala 1996b; McClanahan & Mangi 2000; Roberts et al. 2001), however this is confined to areas very close to MPA boundaries (Fig. 2)(Russ & Alcala 1996b, McClanahan & Mangi 2000), probably due to the limited movement of most reef fishes which are site-attached (Chapman & Kramer 2000). Evidence of this spillover enhancing yield in fished areas is inconsistent. Some studies suggest enhanced catches despite the loss of fishing ground area due to establishment of MPAs (e.g. Russ & Alcala 1996b; Roberts et al. 2001), while others report an overall reduction in yield attributable to the area lost to fishing (e.g. McClanahan & Kaunda-Arara 1995). This may be linked to the size of the MPA; smaller MPAs provide more 'edge' per area for fishers to benefit from spillover (McClanahan & Kaunda-Arara 1995). There has been little effective research on the recruitment effect of MPAs, as it is so difficult to tag and quantitatively trace larval fish. Increased spawning stock biomass within effective MPAs should lead to net export of recruits to fished areas. Models of this dispersal (e.g. Roberts 1997) have suffered from not accounting for the abilities of larval fish to swim and orientate towards reefs in response to stimuli (Leis & McCormick 2002). There is also increasing evidence of moderate to high levels of self recruitment to natal reefs (Jones et al. 1999; Swearer et al. 1999).

Factors Which Have Affected MPA Success

Poaching, perception, benefits, and governance

One of the greatest constraints on the performance of MPAs is poaching through lack of effective enforcement

or compliance. Poaching may emerge from inside the local community, or from outsiders fishing in the area, but is often a result of perceptions of MPAs, lack of management will and resources, and/or lack of involvement of the local community. In most situations, particularly in poorer nations where inhabitants are more dependant on the resources involved, community involvement and support of MPA establishment are essential to MPA success (Russ & Alcala 1999; Elliott et al. 2001; Francis et al. 2002; White et al. 2002). In some nations, for example the Philippines and Fiji, major policy shifts are favouring the co-management or devolution of authority for management of natural resources to local governments and communities (Russ & Alcala 1999; White et al. 2002). Benefits of MPAs to local fishing communities are likely to be delayed. As fishers will be displaced from a portion of their grounds and the stocks are often already overexploited, a programme of education, other fisheries management techniques and development of alternative livelihoods is necessary to complement MPAs (Polunin 2002).

Given the disparity in resource needs of users it is expected that methods of MPA establishment and management will differ between poor and wealthy countries. Although the high level of community involvement needed in MPA establishment may be greater in poor countries, wealthy countries have fast realised the need for public consultation in the design and establishment of new MPA networks (see www.gbrmpa.gov.au for the methods of re-zoning the Great Barrier Reef). However the decisions are often much more 'top-down' and the scientific deliverables can often be much better thought out and incorporated into design. MPAs in wealthy countries can be much larger in area than in poor nations, with less resource dependence, less division of user area and the specific outputs of MPAs often aimed at conservation and tourism benefits rather than local increases in fish yields. Large MPAs established. by governments in poorer nations can come into greater conflict with resource users (Elliott et al. 2001) than small MPAs established with community support (Russ & Alcala 1999).

Biology of species to be protected

Another important consideration when establishing MPAs is the mobility of the organisms it is hoped to protect. Many coral reef fishes and invertebrates are relatively site attached, however larger targeted species of fish may be expected to move greater distances. Target reef fishes may display large intra-reefal movements, but there is little movement between reefs across channels (Davies 1995; Chapman & Kramer 2000). Even apparently transient fish such as the blue trevally show strong site fidelity (Holland et al. 1996). This has huge implications for MPA design. If the objective is to enhance adjacent fisheries production through spillover of post-settlement fish, MPAs encompassing sections of reefs or islands would be preferable to whole reefs or islands; fishery benefits through spillover are most likely to occur within 500m of MPA boundaries (Fig. 2) (Russ 2002). Although many species such as coral trout move large distances within reefs (Davies 1995; Kramer & Chapman 1999), evidence is available for increases in densities of such predators within MPAs that only protect part of an island (Russ & Alcala 1996a; Evans & Russ in press). Furthermore, although home range size may be large, a number of smaller locations may be preferred within that range (Zeller 1997). Conversely, MPAs established for conservation and/or larval export objectives will be likely to produce the best results through protection of whole reefs and/or small islands as units. The use of MPAs to). manage species that migrate large distances is also receiving renewed attention with the protection of areas known to be used by a small portion of the population of certain species thought to have high site fidelity (Gell & Roberts 2003). Beyond movement of adults, many reef fish species utilise different habitats, such as sea-

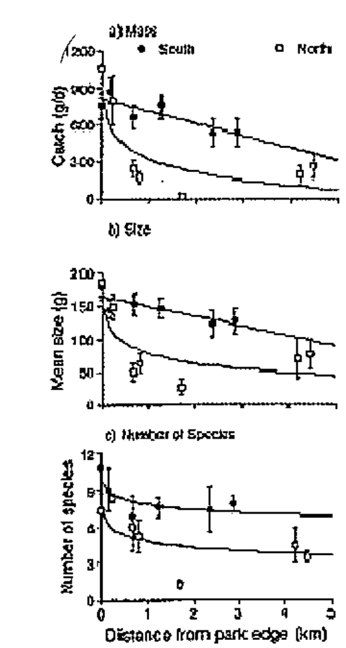

Figure 2. a) total fish catch by mass, b) mean size of fish, and c) number of species as a function of distance away from the park border on both the southern and northern sides of the Mombasa Marine Park, Kenya. From McClanahan & Mangi 2000.

grass beds, estuaries and mangrove swamps, during different life history stages (Nagelkerken et al. 2002; Mumby et al. 2004) and networks of MPAs protecting a range of these 'representative' areas may prove useful for management purposes (see www.gbrmpa.gov.au

Ecological linkages

A long-standing debate in coral reef ecology is fuelled by whether the ecosystem is controlled by 'bottom-up' processes such as variable recruitment (Doherty & Williams 1988) or 'top-down' processes through predation (Grigg et al. 1984). Highly variable recruitment has been shown in some coral reef fish populations (Newman et al. 1996; Meekan et al. 2001), and if common across a wide range of species, may have profound impacts on the ecosystem. Predatory control of sea urchins has been well documented on East African reefs (McClanahan & Muthiga 1989) and is indicated in coral reef fish assemblages (Graham et al. 2003; Dulvy et al. 2004a, but see Jennings & Polunin 1997). Overall, it is likely that both recruitment and predation affect reef fish abundances and assemblage structure. Large-scale oceanic events, such as storms, can have significant impacts on recruitment and thus small MPAs (Polunin 2002). Predation on the other hand may serve to control outbreaking species such as crown-of-thorns starfish (Dulvy et al. 2004b), MPA size potentially influencing the ability of a MPA on part of an island or reef to control such outbreaks.

Design of effective MPAs

MPAs should encompass large proportions of fishing grounds if they are to benefit fisheries, particularly at the scale of whole stocks (Roberts et al. 2003). Furthermore, small MPAs may be more vulnerable to the negative impacts of large environmental perturbations such as storms, diseases and pests (Polunin 2002). However, in the majority of cases, particularly in poorer nations, small MPAs are more feasible, are often community led, improving scope for compliance, and often demonstrate measurable benefits (Russ & Alcala 1999). One of the greatest issues is the displacement of fishers from large portions of their fishing grounds. As highlighted above, in some cases displacement is expected to be compensated through increased yields, as indicated by modelling (Nowlis & Roberts 1999) and empirical data (Russ & Alcala 1996b; Roberts et al. 2001), but in other cases yield has decreased (McClanahan & Kaunda-Arara 1995). These differences may be influenced by MPA size when related to adult species spillover; however, the larval export role of MPAs may prove the greater source of benefit from protection (Russ 2002). MPA site selection based on ecological before sociological criteria has been advocated (Roberts et al. 2003), yet in many cases communities may only wish to place MPAs in unproductive fishing grounds and this placement may be integral to effective compliance. Criteria that would enable MPAs to be designed to optimise multiple objectives would be ideal and networks of MPAs to link source and sink populations of larval replenishment should ensure the widest benefits (Roberts et al. 2003). It is important to highlight the importance of other habitats to life history stages of many species (Nagelkerken et al. 2002; Mumby et al. 2004). The Great Barrier Reef is currently being rezoned to this affect; a suite of 'representative areas' included in the new network of fully protected areas (www.gbrmpa.gov.au).

Conclusions and Future Use of MPAs in Coral Reef Management

Given the number of well-designed empirical studies is few, particularly for the benefits outside MPAs, continued research in these areas should be a priority (Russ 2002). This lack of scientific knowledge, should not, however, delay establishment of MPAs (Russ 2002). The use of protected areas in tourism development and thus as a source of alternative livelihoods should not be overlooked. Research on diver perceptions and tourism related benefits are sorely needed. Although MPAs are a useful management option, they should not be used in isolation. Reducing fishing effort, greater education and alternative livelihoods will all play key roles in the success of a management system. The design of MPAs should take into account the specific objectives, socioeconomics of the resource users and the ecological characteristics of the specific locations. Although larger areas may be preferential, smaller MPAs will often be more practical and prove useful in many situations where users are heavily dependant on the resource. Involvement of local communities in planning, design, establishment and management of MPAs should improve chances of success in the long term.

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The Effects of Terrestrial Runoff of Sediments, Nutrients and Other Pollutants on Coral Reefs[1]

Synopsis

Increasing terrestrial runoff of sediments, nutrients and other pollutants into the sea is a growing concern for many of the over 100 nations endowed with coral reefs. This document provides a brief overview of the known effects of exposure to terrestrial runoff on the health of corals and of coral reef ecosystems. It also describes measures some countries have started taking, as there are considerable economic net benefits gained from an investment into reducing the loss of sediments, nutrients and other pollutants into the sea.

- The main reasons for deteriorating water quality in coastal and inshore marine systems are land-based activities including vegetation removal, soil erosion and fertilizer loss from expanding agriculture, expanding coastal urbanization and the associated discharge of insufficiently treated sewage, and industrial pollution.
- The main direct effects of terrestrial runoff on coral populations are: reduced recruitment, decreased calcification, shallower depth distribution limits, altered species composition (shifting from a more phototrophic to a more heterotrophic fauna), and the loss of biodiversity.
- A number of effects on the wider coral reef ecosystem are also observed and/or discussed, although their links to water quality are more difficult to test. Particularly relevant are: (1) the proliferation of algae that compete with corals for space; (2) increasing rates of internal bioerosion making corals less resistant to storm impacts; (3) increased susceptibility of corals to some diseases; and (5) more frequent outbreaks of the coral-eating starfish *Acanthaster planci*.
- Because terrestrial runoff directly affects coral recruitment, runoff-exposed coastal and inshore coral reefs will take longer to recover from disturbances by storms, coral bleaching and outbreaks of coral predators than reefs in cleaner water. Coral reefs in well-flushed locations are at lower risk of being degraded by terrestrial runoff than regions where the retention of pollutants is high.

The economic costs of failing to control land-based activities are high. However, no universal measures to combat terrestrial runoff exist, instead regions have to develop and costs evaluate separate solutions for each situation. Measures to consider are to (1) raise awareness how actions on land negatively impact the adjacent marine environment; (2) carefully plan land use, and use self-regulation and regulatory frameworks to implement these plans; (3) prevent habitat destruction through education and enforcement; (4) protect riparian and coastal vegetation and wetlands that actively filter out pollutants, (5) imple-ment advanced waste water treatment, (6) monitor and scientifically evaluate the ecological status of riparian, coastal and marine habitats, and (7) develop national and international policies that take into account the economic value of environmental goods and services.

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Links Between Land and Sea

Coastal seas are under growing pressure from land-based sources of pollution as the result of increasing deforestation and associated soil loss, escalating use of fertilizers and pesticides, and discharges of other effluents including domestic and industrial sewage (GESAMP 2001). Model estimates indicate that soil erosion and land-based pollution represents a medium to high threat to 22% of the world's coral reefs (Bryant et al. 1998). The percentage of reefs threatened by terrestrial runoff is up to 50% in countries with widespread land clearing (Bourke et al. 2002). Other forms of deteriorating water quality further add pressure to coral reefs: the models classify 12% and 30% of reefs under threat from marine pollution and coastal development, respectively (Bryant et al. 1998). At global scales, pollution, together with coral bleaching, destructive fishing and overfishing, is rated as one of the main threats to coral reefs (Spalding et al. 2001). At local scales, it can be the single most dominating pressure on the ecological balance in particular of inshore coral reefs.

Coral reefs are most commonly found in clear oceanic tropical waters where they can grow to depths of >40 m. However, coral reefs can also flourish in naturally turbid waters to at least 10 m depth (Yentsch et al. 2002), supporting unique and diverse communities that are not found in clearer offshore waters. Reefs in coastal and inshore waters experience naturally more variable conditions, including higher levels of dissolved and particulate nutrients and siltation and hence reduced water clarity, and more fluctuating salinity, than reefs in oceanic waters, where water clarity is high, siltation is low, and nutrient levels are generally low except during periods of upwelling (Furnas 2003). Coral reef communities naturally change along gradients from terrestrially influenced to oceanic conditions. These natural gradients contribute to the diversity of types of coral reefs found. Large volumes of freshwater and sediment discharges kill corals and prevent coral reef growth, even when systems are unaltered by humans; hence no coral reefs are found tens to hundreds of kilometres downstream of large rivers such as the Amazon (Brazil) or Fly River (Papua New Guinea). Smaller streams can alter reef communities at the scale of hundreds of meters to a few kilometres downstream of their mouths (West and Van Woesik 2001). When watersheds (catchments) from larger landmasses are heavily altered, runoff pathways change, with rapid overland flow over compacted, often bare surfaces replacing slower through flow pathways through vegetation, leaf litter and soil profiles. As a result, their discharges into the sea are intensified and/or spatially extended, enhancing near shore siltation, nutrient concentrations and water turbidity, and adding pollutants such as pesticides, fertilizers, and heavy metals to the coastal zone. Similar processes occur at smaller scales around islands, through alteration of coastal zone vegetation and hydrodynamics, and the increased import of sewage and industrial pollutants associated with urban development.

Water Quality Effects on Coral Populations

The responses of coral populations to sedimentation, turbidity, nutrients and pesticides are reasonably well understood from controlled experiments, and from observations around point sources.

Sedimentation

Direct effects of sedimentation include smothering, energy expenditure for surface cleaning by ciliary action, abrasion and shading of adult corals (Rogers 1990, van Katwijk et al. 1993, West and Van Woesik 2001), and reduced depth ranges (Edinger et al. 2000, Anthony and Fabricius 2000). Thresholds to recover from sedimentation vary between species (Stafford-Smith and Ormond 1992), and increase with organic loads and microbial activities in sediments. They are an order of magnitude lower for coral recruits than for adult corals (Fabricius et al. 2003). Probably the most severe effect of sedimentation is the inhibition of recruitment (Tomascik and Sander 1987b, Babcock and Davies 1991, Wittenberg and Hunte 1992, Gilmour 1999, Ward and Harrison 2000, Harrison and Ward 2001, Babcock and Smith 2002, Cox and

Ward 2002). Sedimentation is therefore considered one of the most widespread contemporary, human-induced perturbations on reefs.

Turbidity

Turbidity that reduces light penetration is often associated with resuspension of sediments, or with enhanced water column productivity. Although corals are animals, they garden within their tissues a large number of single-celled micro algae (called zooxanthellae) that greatly contribute to the corals' nutrition through photosynthesis. For this reason, corals depend on light and clear water to gain energy. Direct effects of enhanced turbidity and chronic siltation on corals are a reduction in photosynthesis and growth, and increase in metabolic costs (Rogers 1979, Rogers 1983; Telesnicki and Goldberg 1995). Consequently, the depth range within which corals can survive or maintain active reef growth diminishes (Yentsch et al. 2002).

Nutrients

Experimental studies and work in areas of nutrient upwelling has shown that dissolved inorganic nutrients negatively affect coral fertilization rates (Harrison and Ward 2001) and rates of coral calcification (Kinsey and Davies 1979, Marubini and Davies 1996). Studies to investigate the effects of elevated dissolved inorganic nutrients on coral growth have yielded inconsistent responses, possibly because many responses are non-linear (Tomascik and Sander 1985): although slightly enhanced concentrations of nutrients may stimulate coral growth (while reducing skeletal density), high concentrations can have the opposite effect (stunting coral growth). This is because high nutrient concentrations increase the density of zooxanthellae in the tissue, hence altering the balance of energy, CO_2 and nutrients transferred between zooxanthellae and host (Muscatine et al. 1989, Marubini and Davies 1996). Many species of coral can however gain nutrients from suspended particulate matter, partly compensating for reduced phototrophy in turbid waters (Anthony and Fabricius 2000).

Other pollutants

Due to the great diversity of contaminants and exposure levels in different areas, it is difficult to adequately summarize the effects of agrochemicals, petrochemicals, heavy metals and other industrial pollutants from mine tailings, refineries, smelters, port operations etc on coral reefs. For example, low concentrations (a few parts per billion) of some widely applied photosynthesis-inhibiting herbicides effectively suppress photosynthesis in corals, seagrass, and other photosynthetic organisms (Scarlett et al. 1999, Jones et al. 2003). Cyanide severely damages or kills corals after a few minutes exposure (Cervino et al. 2003). Heavy metals such as copper suppress coral fertilization at concentrations of a few tens of parts per billion (Reichelt-Brushett and Harrison 1999). Effects of many of the numerous existing pollutants (PAH, PCB, persistent organic pollutants, endocrine disruptors, insecticides, fungicides etc) on corals and coral reef organisms are presently largely unknown, but some of these substances are known to accumulate in the food web and have toxic effects above certain concentrations.

Water Quality Effects on the Wider Coral Reef Ecosystem

The studies listed above document that the reproduction, growth rates and mortality of corals is strongly affected by deteriorating water quality. High turbidity, shading and high particle loads also lead to reduced biodiversity in hard corals and octocorals, due to their differences in tolerance levels (Fig. 1; Tomascik and Sander 1987a, Edinger et al. 1998, van Woesik et al. 1999).

Terrestrial runoff not only affects coral populations directly, but can also have profound effects on other key groups of reef organisms. Establishing causal relationships between ecological responses and environmental conditions is often difficult. Nevertheless, strong circumstantial evidence exists for the existence of links between water quality and the following ecosystem responses (Fabricius, in review): increasing macroalgal abundances; increased internal bioerosion; increased susceptibility to some diseases in corals and octocorals; and changes in the abundance of coral predators.

Shifts from coral to macroalgal dominance

After disturbance such as storms, benthic algae settle on the dead corals and obtain space dominance. Environmental conditions determine whether they continue to dominate space and inhibit coral recovery, or whether corals are able to settle amongst these macroalgae, eventually outcompeting them and regaining space dominance. Under experimental conditions, some macroalgae are nutrient-limited and have a direct growth advantage at slightly enhanced levels of inorganic nutrients (Lapointe 1997, Schaffelke 1999b). Some coral reef inhabiting macroalgae can also grow faster by trapping particulate organic matter in their fine hair-like structures on their surface and using associate nutrients (Schaffelke 1999a). On the Great Barrier Reef, macroalgal abundances increase along two water quality gradients from low to higher nutrient levels (Fig. 1). However, the relationship between macroalgal cover and nutrient status is complicated by the fact that in many areas, macroalgal standing stocks are co-limited by grazing (Hughes et al. 1999, McCook 1999, Szmant 2002, Diaz-Pulido and McCook 2003, McClanahan et al. 2002, McClanahan et al. 2003): hence, macroalgal cover may not respond to nutrients if grazing is intense, or, in reverse, algal carpets can establish even without higher nutrient availability if grazing is low (either naturally or due to overfishing or disease).

Internal bioerosion

Some filter feeders and microalgae bore into the skeletons of live corals and the underlying inorganic reef substratum; these organisms are called internal bioeroders. While some bioeroders are sensitive to sedimentation, the rate of internal bioerosion is higher in areas of high loads of nutrients and particulate matter than in nutrient-poor clear oceanic waters (Rose and Risk 1985, Sammarco and Risk 1990, Edinger and Risk 1996, Holmes 2000). Intense internal bioerosion can reduce the resistance of reefs to storm damage. Some researchers therefore suggest that enhanced nutrient levels may affect overall reef growth not just be reducing coral calcification, but also by increasing reef erosion (Hallock 1988).

Increased susceptibility to diseases in corals

Both prevalence and virulence of certain coral diseases increase when levels of dissolved inorganic nutrients are experimentally enhanced (Bruno et al. 2003). Airborne or waterborne microbes from eroding soils such as Saharan dust have also been linked to greater disease prevalence in corals (Shinn et al. 2000, Jolles et al. 2002). It is however not yet clear to which extent the high levels of disease found in the Caribbean corals and sea fans are affected by water quality, and how big a problem the coral diseases are in other geographic regions.

Changes in the abundance of coral predators

The potential increase in the frequency of population outbreaks of the crown-of-thorns seastar Acanthaster planci through terrestrial runoff (Birkeland 1982, Brodie 1992) represents another indirect effect, and particularly severe effect of water quality on the status of the wider coral reef ecosystem. There is a strong spatial and temporal association between drought-breaking floods from high continental Indo-Pacific islands and outbreaks of A. planci (Birkeland 1982). More A. planci larvae complete their development at slightly increased concentrations of large planktonic algae (Okaji et al. 1997), algae that tend to bloom when nutrient limitation is released. While overfishing of predators of juvenile A. planci can also contribute to higher seastar survival, evidence is strong that nutrification leads to increased frequencies or intensities of crown-of-thorns outbreaks.

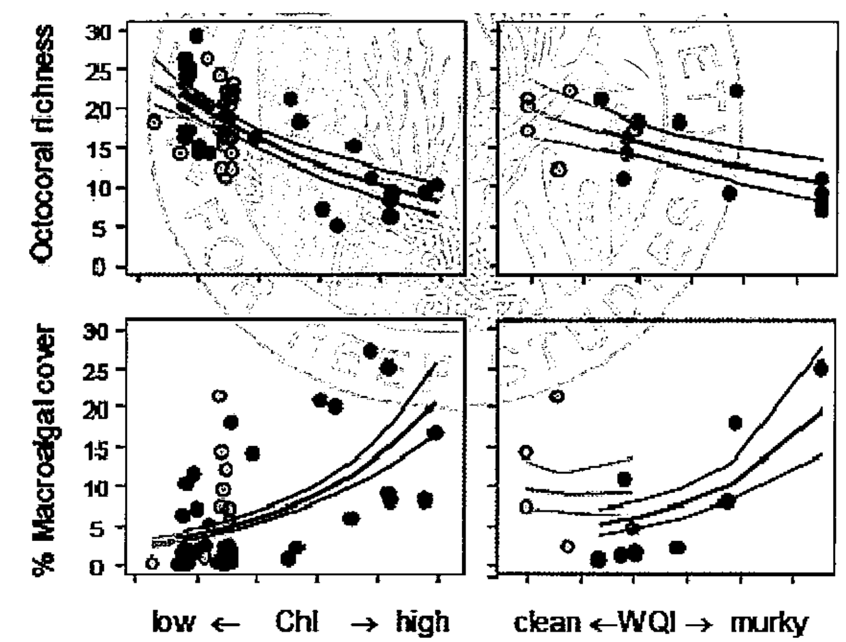
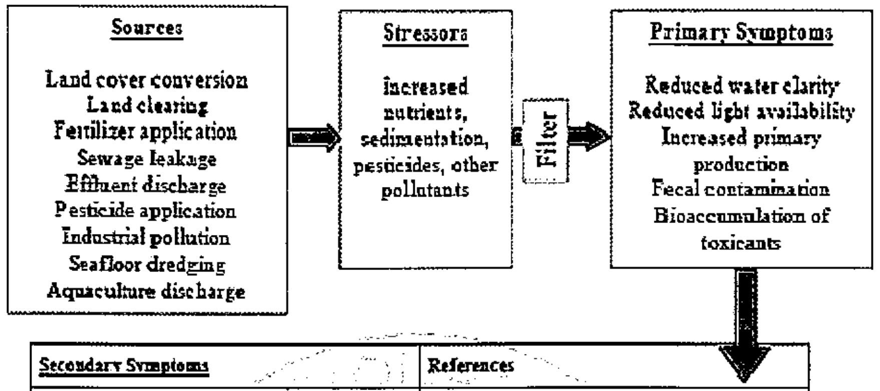


Figure 1. Changes in the taxonomic richness of octocorals and in macroalgal cover along water quality gradients in the Great Barrier Reef; black points represent reefs exposed to runoff from agriculturally used watersheds, gray points are reefs exposed to runoff from watersheds with little agriculture. The chlorophyll data (Chl, left panel) are based on 10-years chlorophyll monitoring by the Great Barrier Reef Marine Park Authority. The inshore water quality index (WQI, right panel) is based on a composite index of concentrations of nutrients, chlorophyll and suspended solids on inshore reefs over 3 years. Adapted from Fabricius and De'ath (2004).

Examples of coral reefs exposed to terrestrial runoff

Field studies on the effects of terrestrial runoff from all oceans have provided compelling evidence of long-term ecological changes in coastal and inshore reefs at local scales in response to excess sedimentation, turbidity and nutrients (Table 1, Fig. 2). At regional scales, causal links between reef degradation and the diffuse pollution from broad-scale land use practices have often been more difficult to demonstrate, because of a lack of historic data to distinguish anthropogenic impact from natural gradients and succession cycles. Regional-scale effects of terrestrial runoff are also often difficult to separate from the effects of other forms of reef use.

Well-studied cases from Kaneohe Bay in Hawaii and from Barbados demonstrate the deleterious effects of chronic eutrophication on coral reefs, and the mechanisms that led to changes. In most cases, factors other than eutrophication were the proximate causes of coral mortality. Thereafter, hard corals failed to re-establish on the affected sites. Only a few cases are described where differential post-settlement survival, selecting for more resistant or adaptive coral species, appeared to be responsible for shaping the coral communities (Wit-



Secondary Symptoms	References
Lower larval production	Tomascik and Sander 1987b, Cox and Ward 2002.
Lower coral recruitment	Smith *et al.* 1981, Hunte and Wittenberg 1992.
Higher incidence of some coral diseases	Bruno *et al.* 2003, Shinn *et al.* 2000.
Lower skeletal density	Kinsey and Davies 1979, Lough and Barnes 1992.
Higher coral mortality	Wittenberg and Hunte 1992, Wesseling *et al.* 2001, Cortes 1994.
Reduced coral diversity, community phase shift	Smith *et al.* 1981, Pastorak and Bilyard 1985, Tomascik and Sander 1987a, Acevedo and Morelock 1988, Edinger *et al.* 1998, Fabricius and De'ath 2001, Fabricius and De'ath 2004.
Enhanced bioerosion	Rose and Risk 1985, Hallock and Schlager 1986, Hallock 1988, Holmes 2000, Chazottes *et al.* 2002.
Enhanced macroalgal growth and biomass	Smith *et al.* 1981, Lapointe 1997, Costa Jr. *et al.* 2000, Lapointe *et al.* 2004.
Higher frequency of outbreaks of *Acanthaster planci*	Birkeland 1982, Brodie 1992.

Figure 2. Schema of potential sources, stressors, primary symptoms, and secondary symptoms directly affecting hard corals and coral reef ecosystems (adapted from Sullivan Sealey 2004). The "filter" represents local conditions that determine the resistance and resilience of a reef to being affected by terrestrial runoff, such as flushing rates, depth of the surrounding sea floor etc (Cloern 2001).

tenberg and Hunte 1992, van Woesik et al. 1999). In Kaneohe Bay, a sewage outfall pipe had caused local severe eutrophication for two decades, however a diversion of the outfall site to an offshore location locally improved the water quality and initiated reef recovery within a few years (Hunter and Evans 1995). Recovery has remained incomplete, possibly because nutrients in sediments are still high and because diffuse discharges from the increasing human population continue to discharge nutrients into the bay (Stimson et al. 2001). In Barbados, sewage discharge and industrial pollution changed the water chemistry along the coast sufficiently to reduce growth and recruitment of some of the main reef building corals (Tomascik and Sander 1985, Tomascik and Sander 1987b). On inshore reefs of the central part of the Great Barrier Reef, coral cover has declined to low levels from a series of unrelated disturbances since 1986, and reef building capacity on some reefs is reduced compared to pre-European settlement times (van Woesik et al. 1999). In two inshore regions, coral cover, hard coral and octocoral coral species richness decrease, and macroalgal cover increases along water quality gradients (Fig. 1; van Woesik et al. 1999, Fabricius and De'ath 2004). Similar studies exist from Indonesia, where coral biodiversity decrease and bioerosion rates increase with increasing water pollution (Edinger et al. 1998, Holmes et al. 2000), and Okinawa, Japan, where coral cover declines along gradients of eutrophication or river influences (Shimoda et al. 1998, West and Van Woesik 2001). These and many other case studies suggest that enhanced sedimentation or eutrophication alter the community composition and slow the recovery of hard coral communities after disturbance events, by substantially affecting coral recruitment. They also demonstrate cases of enhanced bioerosion, reduced coral growth and calcification rates, and hence reefs that erode faster than accrete.

Reefs vary greatly in their susceptibility to damage by poor water quality. Existing field observations from around the world indicate that reefs in poorly flushed semi-enclosed bays or lagoons, and reefs surrounded by a shallow sea floor, are at greatest risk of degradation, probably because materials are retained for prolonged periods of time, extending the period of exposure to more 'chronic' conditions. In contrast, reefs along well-flushed coastlines surrounded by deep water, where terrestrial pollutants are washed out within days to weeks, appear more resistant and resilient against degradation by exposure to high sediment and nutrient loads.

What Needs to be Done?

Coastal and inshore reefs are of high economic and ecological value. They supply food and wave protection for coastal settlements, they are popular destinations for the growing dive tourism industry, and they are unique habitats for a vast number of coral reef associated plants and animals that are not found on offshore reefs.

Despite a growing understanding of the effects of terrestrial runoff on coral reefs, there are often uncertainties in the interpretation of field studies of terrestrial runoff, as a result of paucity of proper river monitoring programs in the Tropics, the under-sampling of extreme runoff events, and the co-occurrence of runoff with other forms of human reef usage. Notwithstanding these uncertainties, governments of many nations have begun to recognize the seriousness of the problem of enhanced discharge of sediments, nutrients and other pollutants into the coastal waters, and accept the existing evidence that sedimentation and excess nutrients harm coral reefs. For example, an extensive review of the current scientific evidence of the effects of runoff on the Great Barrier Reef and the economic implications has now lead to a plan to "halt or reverse the decline in water quality entering the reef" (The State of Queensland and Commonwealth of Australia 2003).

The increase in agricultural production and associated loss of terrestrial, freshwater and marine biodiversity and reduced ecosystem services represents a global problem that deserves urgent attention (Tilman et al., 2001). The problem of terrestrial runoff of soils and nutrients into coastal areas will continue to worsen unless the government, agricultural groups and coastal residents put measures in place to ameliorate this problem: tropical forests are lost at a rate of about 0.8% (15.2 million hectares) per year, mostly due to conversion to agriculture, timber harvest and fires (FAO 2000). Global fertilizer application has increased five-fold since 1960 to 150 million tonnes in 1990 and will continue to increase to an estimated 220 million tones in 2020, especially in less developed countries (Bumb and Baanante 1996). Hence, nitrogen and phosphorus-driven eutrophication of freshwater and near-shore marine systems and exposure to pesticides are estimated to increase 2.4 to 2.7-fold by 2050 (Tilman and others 2001). Similarly, the number of coastal residents without access to sewage treatment will continue to increase with increasing human population density and growing urbanization. Decisive actions are therefore urgently needed to combat the associated losses of terrestrial and marine biodiversity. Government plans should aim at setting targets to halt and reverse the decline in water quality discharged from the land within a set period of time, by reducing discharges from point sources and diffuse sources. The necessary actions required are (modified from GESAMP 2001):

1. To raise awareness how land-based activities can negatively impact adjacent marine environments;
2. To design national and international policies for integrated coastal and watershed management, carefully planning the sustainable use and management of natural resources, and using community-based voluntary self-regulatory and regulatory frameworks to implement these plans;
3. To prevent habitat destruction and the loss of biodiversity through education as well as legal, institutional and economic enforcement measures;
4. To rehabilitate, restore and protect riparian and coastal vegetation, wetlands, and other areas of the watersheds that actively filter out suspended sediments and nutrients; to minimize physical restructuring of the shoreline and to maintain coastal set-backs as defined by UNESCO;
5. To develop options for advanced waste water treatment – this is especially critical for growing cities and on small islands; and
6. To monitor and scientifically evaluate the ecological status and functions of riparian, coastal and marine habitats.
7. To design national and international policies that account for the economic value of environmental goods and services, and to provide for the internalisation of environmental costs.

Unlike global climate change, water pollution can be successfully managed by actions taken at local to regional scale. While most action has to take place on land, some management action in the sea can also enhance the resistance and resilience of coral reefs exposed to runoff. In particular, healthy populations of herbivores and predators will help maintaining control of algal or prey populations that may be nutrient limited; hence good fisheries management and the establishment of fish refuges ("no-take zones") may partly ameliorate some of the effects of deteriorating water quality. In return, coral reefs protected from terrestrial runoff will support higher yields of reef fishes than degraded coral communities with little structural complexity, and may even show higher level of resistance and resilience against pressure from global climate change.

Scientists should be involved in establishing integrated monitoring programs, characterizing water and sediment quality, determining contaminant releases, and quantifying environmental impacts in coral reefs. It is important to note that the information already available often provides a sufficient basis for action, and that action should not be postponed pending additional information (GESAMP 2001). However, monitoring data will help assessing and prioritizing management options, and are essential to test the effectiveness of management actions. An integrated monitoring program should therefore aim at resolving (1) sources of pollutants, (2) rates of transport to the reef, and (3) effects on the reef ecosystem. Detailed guidelines explaining the elements of effective water quality monitoring programs, from the initial design over field and laboratory methods to data analyses and interpretation are available free of charge (e.g., Australian and New Zealand Environment and Conservation Council 2000), and coral reef survey methods are well described (English et al. 2002, Wilkinson 2002). It is important to note that many traditional indicators such as coral cover and fish counts are too unspecific to be useful in detecting water quality impacts. Instead, reef monitoring must focus on early indicators of ecosystem change that are relatively specific to water quality impacts (Jameson et al. 2001), including coral recruitment, recruit survivorship, and abundance and dynamics of algae.

Threshold values of nutrients and sediments are usually not applicable, as responses tend to be dose-dependent or specific to local conditions. Therefore acceptable concentrations of "water quality" parameters and ecosystem properties require careful local definition before guidelines can be set at local or regional scales. However, some tentative sedimentation tolerance limits of 10–30 mg dry weight sediments deposited cm^{-2} day^{-1} have been proposed (Rogers 1990, Pastorok and Bilyard 1985, Hawker and Connell 1989), but as acceptable levels will depend on hydrodynamic conditions, organic loading, and background turbidity, thresholds need to be adjusted to local conditions. In contrast, general water quality guidelines for pesticides and heavy metals may eventually be established since the understanding of ecotoxicological effects of these substances on corals and reef-associated organisms is now beginning to emerge.

To conclude, terrestrial runoff can and will seriously alter and degrade inshore coral reefs. It is possible to successfully control water pollution at local to regional scales; however this requires a long-term commitment by governments and the public. Management solutions must be tailored to local circumstances, and each country needs to develop their own strategies to best combat pollution (GESAMP 2001). Most of the solutions will be on the land, and will include adhering to best management practices to retain topsoil, by protection or replanting of vegetation on steep slopes and along waterways, adequate waste water treatment, and spatial and temporal matching of fertilizer and pesticide application with actual crop demands. Socioeconomic studies unequivocally conclude that the costs of failing to control land-based pollution are enormous (GESAMP 2001); therefore considerable economic incentives exist to halt or reverse pollution of coral reefs from terrestrial runoff.

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Sustainable Fisheries Management in Coral Reef Ecosystems[1]

Synopsis

The sustainable management of coral reef fisheries is challenged by the high diversity of target and nontarget fish and invertebrate resources, poverty, and the high spatial variability in resource production. These complications largely preclude strict species-specific management of stocks, quotas, or human fishing effort, which are preferred restrictions used in temperate, wealthy, and industrial fisheries.

- Restrictions on fishing gear, fish sizes, times and space that are enforced by traditional or indigenous management and corroborated by national and international institutions and policies are more likely to succeed in this environment.
- Gears that are destructive to habitats and catch small fish are easily observed and enforced by cultural traditions and national laws. Nonetheless, even fairly low levels of fishing with non-destructive gear will reduce top-level carnivores and the maintenance of their populations will require closures to fishing in time and space.
- Closed areas may range in sophistication and cost from areas that are viewed as too dangerous to fish by virtue of existing technology or tradition to highly managed tourist or enforced wilderness areas.
- The globalization of coral reef fisheries products is often responsible for excess and unsustainable harvesting and needs to be discouraged, regulated, or stopped depending on the state of the resource. National and international laws and management institutions need to support local efforts; culture and institutions to maintain a local balance between resource production and consumption and discourage export and globalization of the resource.

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Introduction

Sustainable use is the concept that resources should be used in way that there is a balance between resource production and human consumption such that harvesting will not reduce future production and options for resource use. Sustainable management therefore requires a shift in focus from short- to long-term use and profits, and places importance on sustaining species with potential future uses. It is also closely aligned with ecosystem management concept where resource use is expected to maintain the many ecological processes and diversity of the utilized ecosystem while managing for multiple present and future needs of people. These concepts are generally acceptable and desirable by most members of society but the problem with implementing these concepts is that they can frequently conflict with the daily practices and desires of the individuals that use resources, which are frequently focused on minimizing effort and maximizing short-term harvests and profits (Aswani 1998). Further, the continual improvements of technology and increases in human populations have produced harvesting and marketing potential beyond the production potential of most ecosystems. Coral reefs are no exception but because they are often viewed as a "common-pool resource" with exceptionally high biological diversity and potential uses they pose special problems for management.

The discussion that follows will outline some of the characteristics of the coral reef ecosystem and resource use and suggest ways that these characteristics can be managed for sustainability of the harvest and the ecosystem. The challenge to describe and present useful recommendations is considerable given that over 100 mostly tropical, poor, and culturally diverse countries have coral reef fisheries that range from subsistence gathering of intertidal snails to industrial trawl fishing and the export of luxury items. Consequently, there will ultimately be a need to gather information and develop management systems sufficiently useful for specific people and coral reef ecosystems but this does not preclude the value of developing global policies and guidelines for programs of study and management that can assist site-specific management objectives. This, therefore, is the primary purpose of this short overview of fisheries sustainability.

The Coral Reef Fisheries Environment

Coral reefs are limited to tropical environments that experience high light, water temperatures and water motion, and low nutrients, land-based influences or pollution. The coral reef environment houses many species because corals skeletons, both live and dead, provide refuge for fishes that find protection from predators among the crevices and hollows provided by coral. The reef is also productive but in many places the production is less than the demand by consumers that inhabit the reef and many fish travel away from the coral reef to find additional food. Consequently, many fish use the coral reef as a home where they find refuge after they return from foraging in more distant seagrass, mangrove, and other ecosystems. This high concentration of fish makes them excellent fishing grounds and are, therefore, a target habitat for fishermen.

Production and Its Limits

One of the curiosities of the coral reef ecosystem is the high productivity of the plants and algae but the low net production of fish (Nixon 1982). The benthic algae production rivals agriculturally intensive and productive systems such as sugar cane but humans can use less than 1% of this production in the form of fisheries (Hatcher 1997). This occurs because of the high internal demand for this production by the coral reef species themselves such that most coral reefs maintain a balance between production and consumption, with only small excess that can be exported or used by humans. Other ecosystems, such as oceanic up-welling systems can produce nearly 50 times more fish than coral reefs for each unit of algal production. Consequently, coral reefs should not be seen as a source for fisheries production for global trade, but rather as a repository of biological diversity. Nonetheless, coral reefs do support important fisheries for tropical people with reported yields ranging greatly from 0.5 to 50 tons per kilometre per year (Dalzell 1996). The average yield from over thirty fishery studies is around 8 tons per square kilometre and may be near the maximum sustained yield but the variation around this mean is larger than the mean itself, suggesting high variation among study sites and difficulties in making reliable estimates and recommendations.

Estimated yields vary greatly depending on the fishing gear, effort and its history in the coral reef. For example, in lightly fished reef areas, such as the remote Chagos Islands of the Indian Ocean, the catch per person is around 60 kilograms per day (Mees 1999) whereas heavily fished reefs in Kenya produce around 3 kilograms per person per day (McClanahan and Mangi 2001). Ironically, the sustainable yields from the Chagos and Seychelles have been estimated at the low end of production between 0.10 and 0.22tons per square kilometre where as the Kenyan reefs produce around 5 tons per kilometre and have potential for higher production if the high fishing effort could be reduced. The differences between these two areas are primarily due to the fact that most of the Indian Ocean island fishery is in deep water, up to 150 m deep, uses non-renewable resources and refrigeration, and the fishery is selective while in Kenya the fishery is less than 10 m deep, uses renewable resources, and is unselective. Consequently, water depth, aerial extent, technology of the fishery and different histories and selectivity of fishing create difficulties for estimating resource productivity and making precise recommendations on maximum sustained yields. The catch per person is the most frequently collected statistic for coral reef fisheries but, by itself, is not very helpful in determining the maximum sustainable catch, as it always declines with increased effort.

To practically estimate the maximum sustained yield for specific coral reefs without relying on the many assumptions of the equations and models used by fisheries scientists it is necessary to monitor the catch on a per unit area basis over time. When catch per area rises there is the potential for further catch but when declining the maximum sustained yield has been exceeded. Consequently, one of the simplest ways to manage a fishery is to reduce effort whenever the total catch for a specific area declines. Catch per area has a few problems that must be acknowledged in order to avoid the common problems that lead to fishing beyond sustainable levels. The two most common problems are that the both the effort and area that the catch is measured from is often not constant over time unless carefully checked. It is possible for the total catch at a landing site to be constant or increases far beyond the maximum sustained yield of the local fishery because the fished area increases and fishers are expending more daily effort. In a declining fishery, fishers will travel further and fish longer and this makes it necessary to change the effort and area parts of this calculation to get unbiased catch per areaestimates. If these factors are considered and the conditions of the environment that influence production do not change greatly between years, than monitoring the catch per area can give good estimates of sustainable fish yields.

Ecological Influences on Production

Light, water movement, nutrients and the aspects of the reef ecology such as the cover of coral and algae and the abundance of herbivores influence production by algae and subsequently coral reef fisheries. Consequently, where light penetration is reduced by depth or dirty water coral fisheries yields are also expected to decline, which is one of the reasons for maintaining clean seawater. The full consequences of dirty water are not that well understood but they do include reduced growth rates of corals and increased decay rates of the dead skeletons, which will reduce the refuge available for fish. There may be other unexpected influences of dirty water such as increases in coral and fish diseases.

Two important aspects of the coral reef community that influence production is the coral cover itself and the herbivores. Coral has lower consumable production than some of the common forms of algae that dominate reefs where herbivores regularly forage. Similarly, algae that are not regularly foraged have lower production than algae that is frequently foraged. Consequently, a very high dominance of coral or low levels of herbivores can reduce production and influence fisheries yields. Coral provides refuge for coral reef fish and their needs to be balance between cover by productive algae and corals to achieve both the production and refuge required by fish. For this reason, reefs with intermediate levels of coral cover of between 25 and 50% of the bottom are likely to be optimal for sustaining high fisheries yields. Fishing gear and methods that destroy coral will reduce the available refuge for fish and fisheries yields. Because many herbivores are needed to keep the production of the algae high there is a need to protect or sustain these populations.

In some cases heavy fishing results in a proliferation of species that influence reef production or refuge. Examples include coral-eating starfish and snails and herbivorous sea urchins that appear to proliferate in the absence or low numbers of predatory fish such as triggerfish, wrasses, and emperors (McClanahan 2000, Dulvy et al. 2004). The loss of coral cover is expected to reduce the abundance of fish that require it for refuge. In the case of sea urchins, very high numbers can eat virtually all of the algal production and prevent it from being utilized by other species. These species, at low numbers, are part of healthy reef ecosystems but at high numbers they become pests and undermine the health and fisheries production of reefs. High numbers of these pests are an indicator of unsustainable fishing and this recognition can act as a basis for increasing restrictions on resource-use.

Catch and Effort Limits

Management activities are often focused on reducing catch and effort in the face of increasing numbers of people entering the fishery with more effective technology. Management has six basic options. These include restricting 1) the numbers of people or boats fishing, 2) the time allowed for fishing, 3) the fishing area, 4) gear or technology, 5) the sizes that can harvested, and 6) the species being selected. Each or a combination of these alternatives will help to limit short-term harvesting in favour of sustaining long-term yields. In many cases more than one if not all of these options are needed to sustain the fishery, but what is critical to their success is the acceptability, adoption and enforcement success of the options.

Effort

Constraining effort by restricting the number of people or boats is one of the most common management systems that are employed by government fisheries departments. Requiring fishing and boat licences and adjusting the number of licences or the fee for a license are common restrictions. Where fisheries departments and associates are able to patrol and check for licences these restriction can have moderate success but in most fisheries the chances of being caught are minimal and if fishermen do not feel compelled to comply with government restriction, common to many poor tropical countries, there is poor compliance and enforcement and widespread disregard for the licensing system (Sutinen and Kuperan 1999). This has led to some well-earned cynicism toward this method of restriction and greater hope for catch limits, closed areas, gear restrictions, and community or local social control.

In nations with sports and industrial fishing, failure to sustain fisheries with the above system has often resulted to a switch towards a license for the maximum quotas or wet weight of fish where the sustainable net off take of the target species is calculated each year. If the catch is landed at a monitored landing site than it is possible to control catch by this method but in tropical artisanal fisheries where catch is landed at many small sites along an undeveloped coastline it is impractical to monitor catch of individual fishers who may typically catch less than 10 kg per person per day. This has led to recognition that local social or community control may be one of the better options for managing coral reefs fisheries (Bunce et al. 2000).

Area

Closing areas to fishing is also seen as an option for fisheries management (Russ 2002) and these have been used by people with traditional management systems where closure ranges from areas inhabited by spirits, as believed by some traditional African people (McClanahan et al. 1997), to areas restricted for harvesting only during feasts when large quantities of meat are needed, as managed by many Melanesian people (Cinner et al. in review). These area-management systems are considerably different from the modern image of marine parks where tourists are charged park fees by government or private business authorities to enter and the two are not often socially compatible, despite both closing areas to entry for fishing and having potentially similar ecological consequences (McClanahan et al. 1997).

Closed areas have the added benefit of protecting fish and the other components in the ecosystem and have, therefore, received a good deal of attention and excitement as tools for achieving both fisheries sustainability and ecosystem management (Allison et al. 1998). They do appear to increase the density, weight and number of species of fisheries target species (Cote et al. 2001, Halpern 2003) when they do work, but despite the creation of many closed areas only a moderate number have achieved their management potential (Kelleher et al. 1995) and going from government gazettement to full compliance is complicated by many hurdles that seem to be overcome most frequently in areas with high levels of nature tourism (McClanahan 1999). Nonetheless, because some coral reef species are slow-growing and slow to recover from fishing (Goeden 1982,

McClanahan 2000) closed areas may be the only way to insure the persistence of these vulnerable populations and the full range of closed areas needs to be encouraged. The types of closed areas will depend greatly on the socio-economic conditions of the sites and should be flexible and utilize systems that are financially sustainable. Large closed areas may be preferable but may only succeed where nature tourism and the economy can afford them, while small-scale and low-cost alternatives will succeed where there is local support but poor external funding.

Gear and size

Increased technological advances in fishing gear is leading to unsustainable harvesting of fish in many areas but even among less technologically advanced fisheries the types of gear used can also result in destruction of habitat and unsustainable fisheries. In coral reefs, a number of gear types are destructive to reef habitat and should be discouraged. These include nets that are dragged, have heavy weights on the drag line, heavy traps made with slow or non-degrading materials, explosives, poisons, and any method that breaks coral to scare or extract fish.

Less obvious is the fact that seemingly different gears can compete for similar resources. As catches decline, the gear that extracts the smallest size and most diverse fish resources may be the "better competitor" and may reduce the catch of other gear types that select larger and more species-specific targets. Well-managed fisheries should have a mix of gear that insures that all target species are utilized but without accelerating competition between gears for smaller fish. This most practically requires that mesh size of gears, including the various nets and traps, have similar meshes that lean towards catching the larger size classes of most species after they have reached their asymptotic size and sexual maturity.

Gear that catch sizes smaller than the alternatives should be eliminated from the fishery or modified to insure no gear has a competitive advantage based on the sizes of caught fish. These generally require constant vigilance by the fisheries managers but fortunately gear are easily seen and evaluated and, if needed, confiscated. Gear use is also often grounded in traditions that can be enforced by culture and laws and this makes them one of the easier restrictions to reach consensus on and enforce.

Species

Restrictions on species are not commonly used in the tropics because of the large number of species and the lack of knowledge on which species require restrictions. Nonetheless, modelling studies of functional groups suggest that choices that fishermen make concerning the catch can greatly influence total yields and ecological processes (McClanahan 1995). In some cases not fishing one functional group such as sea urchin predators, can increase the total yields by insuring that algal production is channelled into herbivorous fish and not into unharvested sea urchins. The evolution of fisheries is, however, to be selective, often focusing on the high-level predators but eventually fishing species further and further down the food chain (Pauly et al. 1998). This maintains the total catch over time even as effort increases beyond what may be sustainable for some top-level predators and slow-growing species. This suggests the need to place restrictions on these vulnerable species. Restrictions on fishing of spawning aggregations, where many of the carnivorous groupers and snappers congregate for short periods of time to breed is one clear example. Unrestricted fishing of these aggregations can quickly reduce their populations and interfere with their reproduction (Sala et al. 2001). Further, as mentioned above restrictions on some specialist predators of sea urchins and starfish, such as triggerfish in the genera Balistes, Balistoides and Balistapus or wrasses in the genus Chelinus, and many of the parrotfish in the genus Scarus, Sparisoma and Chlororus are prime candidates for special status and species-level restrictions due to their important role in coral reef ecology.

The Socio-Economic Dimension

Social, cultural, and economic forces will often determine the success of the restriction options and the challenge for management is to find the right mix of limits for the particular human environment. Many management systems in the past have focused on only a few of these options and if these options are not acceptable by fishers or difficult to enforce there will be poor compliance and success. Consequently, it is recommended that the attitudes and feasibility of the various options be explored early and repeated at intervals during the management process through interviews and public meetings. Once the most acceptable options have been identified, the chances of adoption, compliance and success will improve. Once restrictions are established and their failures and successes have been documented, managers can begin the process of adding and modifying restrictions. This process of including users and their attitudes in the decisions and adaptive management process is likely to build the social capital required for sustainability (Pretty 2004).

Information and Monitoring

Information appropriate to the scale of the resource, their users, and its management is a primary ingredient for successful management (Dietz et al. 2004). Conflict resolution, compliance, and building support and adaptation all require that the information is appropriate for decision-making. The level of this information will vary from the most basic concepts of fisheries and ecosystem management to more sophisticated and holistic databases on fishers, the resource, its use and models of their interaction and probabilities of associated outcomes under various scenarios.

In some cases, fishers are not aware of modern fisheries and ecosystem management and the information they need to change unsustainable practices can be as simple as the recognition that fishing effort and fish abundance are related or that a particular gear is destructive to fish habitat. Once fishers are aware of these relationships there is increased chance that they will adjust their behaviour, management and gear towards more sustainable use. In more sophisticated management environments the outcomes and risks of each management scenario may be calculated and fine tuned estimates of probabilities are required. In many cases, however, resource users make decisions based on opportunities for short-term profits and it is the role of managers and society to instil an ethic of compliance that can buffer this behaviour and the consequent fisheries tragedies.

Because decisions are based on multiple conflicts and desires it is best to collect information on a number of aspects of the fishery, not just the fish or the ecosystem but also the socioeconomic environment. This reduces the chances that unexpected consequences, surprises or externalities will disrupt management activities. For example, unemployment or prices of fuel, gear and fish could be as important as fish stock estimates in the decisions made by individuals, politicians or managers. If information about the resource is lacking the decisions may be made on existing economic information, which can be dangerous when resources are depleted. In many cases the resource user has informal but invaluable information about resources that needs to be part of the decision-making environment (Johannes 2002), but often needs to be distinguished from political positions.

Monitoring, or the collection of information over time, is particularly useful when testing for the long-term effects of specific management systems and to generate information that can evaluate the effectiveness of management. In an optimal management environment, monitoring data would be continuously collected and soon result in changes in management. In practice, there is often missing information, lags in time and compliance with management regulations. The challenge to managers is to find the right mix of information, stakeholder involvement, and management action that will facilitate adaptive responses. Additionally, in many of the poor fisheries that are managed at a very local level, there is a need for simple information collection and management decisions. For example, if a particular size or catch per day of a key target species is below a certain level than this target species would be banned from fishing for a period before testing for this threshold at some later date. Simple management heuristics or thresholds that have been established from prior scientific studies or the experiences of resource users may be one of the better hopes for managing small-scale coral reef fisheries.

Sustaining the Ecosystem and Diversity

Given that it is possible to have a sustainable fishery within a degraded ecosystem and environment it behoves the public and managers to look beyond the mechanics of biomass extraction to the larger issues of the ecology and diversity of the fishing environment. Continuous and long-term fishing of an ecosystem is likely to change the ecosystem significantly in favour of fast-colonizing and growing species that are tolerant of frequent disturbances. These species may be able to maintain high yields into the foreseeable future but there may be a loss of many important components of the coral reef ecosystem. For example, many degraded reefs may be replaced by rubble or seagrass ecosystems that can have productive fisheries but support only a fraction of the species diversity. Coral reef ecosystems are composed of a high diversity of species with life histories considerably different from those that will be selected by the harvesting systems. The challenge is, therefore, to not be complacent with simply achieving fisheries sustainability but also sustaining the ecosystems and all of its components. Maintaining all components of the ecosystem maintains future options and unforeseeable consequences of the changing environment. This has been one of the arguments in favour of closed or reserve areas but there may also be ways that fishing itself can be encouraged to maintain this diversity. As mentioned above, fishing methods that are destructive to coral habitat or eliminate species through destruction of their breeding aggregations will not encourage the broader goal of ecosystem sustainability and should be discouraged.

Global Influences

Coral reef products such as shells, shark fin, sea cucumber, live rock, food fish and valuable invertebrates such as conch and lobster, and ornaments are part of the global trade environment. The globalization of these products has created a demand beyond what is locally sustainable. The trade in coral is presently included under CITES Appendix II and requires permits. Many of the other coral reef products that are equally vulnerable are, however, not well regulated or the extent of their influence on coral reefs is poorly understood. Trade of these products should be undertaken with caution and after some estimates of populations of these species have in their natural environment and the methods used to collect these species are not destructive to habitat. Greater restrictions on trade will improve chances that the species are monitored and protected.

Recommendations

The global value of coral reefs is their high biological diversity and they should be managed for this diversity rather than as a source of food or luxury products for the global trade. Nonetheless, many tropical people rely on coral reef fisheries and management should seek to maintain a local balance between resource production and consumption. This can be achieved by restricting trade of coral reef resources to those species with populations that have been estimated and determined to be above certain ecological viable population thresholds. Further, temporary local restrictions should be placed on species below asymptotic or reproductive sizes. Some species such as some triggerfish and parrotfish species play an important role in coral reef ecology and should not be harvested. Local management can also benefit from thresholds that stop fishing when total catch per area declines or when pest species exceed thresholds. Local, national and international leaders should discourage and ban gear that is destructive to habitat. Restrictions on gear that catch small individuals should be discouraged and management should promote a mix of gear that do not compete for similar resources or smaller sizes of individuals. Management needs to adapt to local conditions and attitudes in a way that management systems are embraced by fishing cultures and self-enforced. Simple adaptive learning heuristics and thresholds for restrictions are needed and should be encouraged such that management can be simple, cost effective, and managed by local authorities.

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ISRS Statement on Diseases on Coral Reefs

Diseases of corals and other organisms are having significant, negative impacts on the structure and appearance of coral reefs. On some reefs, the effects of disease have been of a similar magnitude to more familiar disturbances, such as outbreaks of the crown-of-thorns starfish in the Indo-Pacific and worldwide coral bleaching associated with elevated sea temperatures. A new scientific awareness of diseases on coral reefs leads to a host of questions about the novelty of recently discovered syndromes, the importance of observed trends toward increasing infection rates, and the extent to which human activities are responsible. This statement, issued by the International Society for Reef Studies (ISRS), summarizes current knowledge on the subject. It was compiled by an *ad hoc* group of scientists in ISRS, composed of individuals who are directly or indirectly considering disease as part of their research programs.

Disease is a natural process that has been poorly studied in the oceans because of its ephemeral nature. Epidemics in animal populations, called epizootics, are a serious threat to the health of coral reefs worldwide. Recent observations of epizootics affecting sea urchins and corals show that diseases on reefs can devastate their target populations and act as agents of rapid and dramatic community change. Marine pathologists and microbiologists are attempting to identify the causes of infection, but the pathogens responsible for most diseases affecting reef organisms remain elusive. These difficulties complicate efforts by scientists and managers to study outbreaks and to determine if control measures are warranted. It is becoming clear, however, that human activity is at least partially responsible for disease outbreaks on coral reefs over the past decade.

Corals are colonial animals related to sea anemones. They lay down the limestone foundations of coral reefs. Coral reefs are important because they protect tropical shorelines from damaging storm waves, and because they provide habitat for many of the fish and invertebrate species that feed a substantial proportion of the world's population. Like all living organisms, corals are prone to diseases of various sorts. A few long-term ecological studies of coral reefs suggest that the incidence of disease has risen over the past several decades. In most cases, however, historical information does not exist, and it is difficult to determine whether the increase in disease is real or simply a reflection of increased research activity. Recent scientific reviews list four to six confirmed coral diseases in the Caribbean region alone; other estimates, based only on observed symptoms, run as high as fifteen. Bacteria, fungi, and cyanobacteria ("blue-green algae") are known to cause diseases in corals. Sick and dying corals are cause for concern, because coral death slows the rate of reef construction. Reefs devastated by disease (or by other causes of coral mortality) may not be able to keep up with sea-level rise, which is naturally slow but may be accelerating due to global warming. As reef growth slows, the processes that degrade reefs assume greater importance, and fish and other seafood resources decline as well.

Three coral diseases—"white-band," "black-band," and "plague"—were first reported in the Caribbean in the 1970s. The first documented, regional-scale epizootic, however, affected the long-spined sea urchin, *Diadema antillarum*. In 1983–84, a disease carried by ocean currents, and possibly in the ballast water of ships, killed more than 95 percent of the *Diadema* throughout the Caribbean. This epizootic clearly demonstrated that diseases can have major impacts on reef ecology. Before its mass mortality, *Diadema* was an important herbivore. It ate fast-growing fleshy algae (seaweeds), keeping space free for corals to survive and grow. After the urchins died, algae increased dramatically on many Caribbean reefs. They colonized corals that had been killed by hurricanes and by diseases, particularly white-band disease. Since then algal growth has been so rapid on some reefs that the surviving corals have been unable to continue growing, and small, newly-settled corals are simply being overgrown and killed.

Although the infective agent of white-band disease remains unknown, there is some evidence that it is bacterial. White-band disease infected populations of staghorn and elkhorn coral (*Acropora cervicornis* and *Acropora palmata*) throughout the Caribbean region in the 1980s and 1990s, inflicting enormous losses. Because *Diadema* also disappeared, algae rapidly colonized the dead coral skeletons. As a result large areas of Caribbean reefs are now covered with algae and have been for over a decade. Paleontologists working on fossil reefs in Belize recently uncovered evidence that the epizootic of white-band disease is without historical precedent: a regional dieoff of staghorn coral has not occurred previously in at least the past several thousand years. Staghorn and elkhorn corals are major constructors of reef framework. Their loss has dramatically altered the ecology of Caribbean reefs and may slow future rates of reef growth.

Many marine scientists suspect that human activities, such as pollution and changing patterns of land use, promoted the spread of white-band disease in Florida and the Caribbean. There is little evidence for a human connection, however, other than the historical novelty of the outbreak. Eutrophication, or nutrient pollution, may be an important source of stress to reef organisms. This stress may compromise disease resistance, allowing infections to take hold and new diseases to emerge. A fungal disease of sea fans appears to provide a link to human activity. The fungus, *Aspergillus sydowii*, has infected large populations of sea fans in the Florida Keys and throughout the Caribbean. *Aspergillus sydowii* is thought to be a land-based fungus that has invaded the marine environment via the sediment in terrestrial runoff.

Reliable information exists for two other diseases: black-band disease and "plague type II." Black-band disease, caused by a consortium of bacteria (including cyanobacteria) attacks and kills massive, head-forming corals. Black-band disease could pose a serious threat to populations of brain and star corals, which, like the *Acropora* species, are important components of reef framework in the Caribbean. Like black-band disease, plague type II attacks and kills head corals. Plague type II was first reported in Florida in 1995, but it has now been observed elsewhere in the Caribbean. In this case, rigorous microbiological work showed that the disease is caused by a single bacterium, a new species of *Sphingomonas*.

Epizootics are killing corals and many other important species on reefs of the Pacific, Indian, and Atlantic Oceans. Black-band disease and white-band disease have now been identified on reefs throughout the tropical Indo-Pacific, including the Red Sea, Mauritius, the Philippines, Papua New Guinea, and the Great Barrier Reef of Australia. In the Arabian Gulf, the newly discovered yellow-band disease is affecting up to 75 percent of the coral colonies in local populations. In addition, diseases of algae, sponges, and fish have been and continue to be identified.

Reefs throughout the world were stressed by unusually high sea temperatures in 1997–98, and the worldwide episode of coral bleaching that resulted may render corals more susceptible to disease. In the Mediterranean Sea the bacterium *Vibrio shiloi* is the causative agent of bleaching in the coral species *Oculina patagonica*. Disease outbreaks have been linked to predation by coral-eating snails in the Red Sea. In general, however, the connections among bleaching, predation, and disease remain obscure.

The role of disease on coral reefs and possible interactions with environmental influences should be a research priority over the next several years. Despite the frustrating inability to identify pathogens in most cases, reef scientists have detected symptoms that could represent over a dozen new diseases. Diseases are now recorded as part of standard reef-monitoring programs throughout the world, including the Caribbean Coastal Marine Productivity (CARICOMP) Program, the worldwide Reef Check, the Atlantic and Gulf Reef Assessment (AGRA) Program, and a variety of government and private programs in Australia.

Because corals grow slowly, live for decades to centuries, and reproduce sporadically, today's diseases will probably have consequences that reach far into the future. Multidisciplinary efforts combining microbiology, coral physiology and pathology, ecological monitoring, and paleontology will be necessary to understand the causes and consequences of these diseases and to devise management strategies in response. The International Society of Reef Studies endorses existing government and private funding of multidisciplinary programs to promote research on the changing nature of coral reefs. The Society recognizes the need for an increased level of support if the many threats to reefs worldwide are to be understood and mitigated.