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Paradise lost: how marine science failed the world's coral reefs

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Abstract. The response of the coral reef scientific community to the present global crisis in coral reefs is here compared with response times and response patterns of scientists in two previous international environmental crises: eutrophication of the Great Lakes and acid rain in the Northen Hemisphere. In both these previous crises, less than a decade passed from first appreciation of the problem to development of identification/evaluation/mitigation frameworks that were useful in a policy context. Key elements were avoidance of arguments over methods, genuinely multidisciplinary teams, and the presence of respected, technically trained managers. By contrast, twenty years after identification of the major stresses on reefs and description of the major monitoring strategies, there is no process–response model in place, in any country, equivalent to those produced in response to eutrophication of the Great Lakes or acid rain. Reasons for this failure include, but are not limited to: dominance by one field of science, biology; lack of competent scientific managers; and emphasis on monitoring programmes, with no clear idea how the results will be used.

Introduction

This paper examines how scientific research, scientific management and government policy do or do not work together. I believe that, for coral reef ecosystems, these elements have not meshed as smoothly as in some previous cases. I present here my analysis of this failure.

By 'failure', I mean that there has been an unacceptably long delay from identification of the problems with coral reefs to establishment of necessary monitoring, evaluation and remediation protocols. Marine science, in this context, is taken to include academics, scientific staff of multinational development agencies and government scientists in the relevant countries.

It should also be made clear at the outset that some environmental problems are simply intractable at the present time. In some countries, the pressures from industrial development and population growth are so great that there is not much that can be done at this time to prevent degradation of nearby reefs. There may be environmental problems for which the scientific frameworks for monitoring, evaluation and mitigation are well worked out but cannot be applied for economic or political reasons. These do not constitute a failure of science, but rather a failure of society.

A successful approach to dealing with environmental problems may be seen as a stepwise process:

(1) Identification and awareness of an environmental problem. This may stem either from public perception of a problem or from results of investigative scientific research. In either case, one may consider that the meter starts running as soon as knowledge of a problem becomes widespread. (Many such environmental problems are brought to our attention via observed impacts on some element of the biota; this demonstrates the utility of bioindicators.)

(2) Accumulation of resources. There needs to be scientific critical mass in order effectively to address the problem.

(3) Monitoring and research. Ideally, these two activities continue in parallel. Monitoring should be a concerted activity directed towards detecting changes in a biological system and should be integrated with research that attempts to identify (and perhaps ameliorate) the stressors producing these changes. Research on stresses on biological systems is more effective when combined with a time perspective obtained from monitoring, and those monitoring programmes are most effective which focus on detecting the most likely sources of stress.

(4) Management–policy interface. This step is critical to dealing with any environmental problem, and it is this step which most scientists point to as causing the most delays and confusion. This is not necessarily the case.

In reaching my conclusions, I will draw parallels between scientific responses to present pressures on coral reefs and large-scale environmental problems in the recent past that have called for concerted action. It must be acknowledged at the outset that reefs possess unique characteristics which affect the degree to which they may be described and managed. For one thing, to belabour the obvious, reefs are submarine ecosystems. This limits the ease with which research programmes may be mounted. More important in scientific management terms, however, is the fact that coral reefs are multinational, with most reefs occurring in the lesser-developed countries. It would certainly be unfair to expect nations with few resources to mount expensive monitoring and evaluation programmes. Of the 100-odd countries that possess coral reefs (data from Wells 1988*a*, 1988*b*, 1988*c*), about 90% can be classified as developing nations. The remainder may be classified as under the jurisdiction of

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a small number of developed nations: United States of America, Australia, Israel, Japan, France and the United Kingdom. (To this list could be added Mexico, a nation with excellent coral reef scientists and one whose economic development is relatively more advanced than the majority of its neighbours in Latin America.)

The major stresses acting on reefs worldwide are comparable among nations. These stresses are, in no particular order of importance, siltation, sewage, destructive fishing techniques and urban/industrial development. One may therefore look to the developed nations to produce research, policy and legislative frameworks that may be transposed to other parts of the world.

Any parallels drawn between present reef programmes and past examples of previous environmental programmes are of necessity imperfect. To obtain the best possible comparisons and contrasts, programmes chosen for comparison should have the following attributes.

- The process–response–decision sequence must have occurred fairly recently, within the latter half of the 20th century. This ensures that scientific and management techniques will be comparable.
- The examples must be multinational in scope, involving a potential population base in the millions. This brings the scale of scientific endeavour and management problems into the scale with which coral reef programmes must deal.
- Ideally, there should be elements of tourism, fisheries, sewage disposal and industrial development. All of these affect reefs, and bring with them their own levels of complexity.

The two examples I will discuss are eutrophication of the Great Lakes, involving Canada and United States of America, and the impact of acid rain in the Northern Hemisphere, involving more than a dozen countries on the top half of the globe. The scientific literature on these topics would fill a small library: this paper can provide only the sketchiest of outlines. A few key references are appended. Much of the discussion is abstracted from interviews with senior scientists from several nations, with experience in both of these examples. In some cases, I have quoted directly from the interviews.

Selected examples

Eutrophication of the Great Lakes

Response to eutrophication of the Great Lakes began in the mid 1960s following pressure from a concerned public, generated by some good investigative journalism. There was a period of about five years from the first perception of the problem to the first concerted action.

The result was the world's largest international watershed study, which was run by some highly respected scientists. The umbrella organization was termed PLUARG (Pollution from Land Use Activities Reference Group.) Questions of methodology were handled by subgroups. It was understood early on that, in international work, there will never be agreement on methods. Quality assurance protocols were erected to allow comparison of results produced by different groups: 'What you need is not common methods but common results'. Management emphasized top-down directed research**,** not curiosity-driven academic research. 'When PLUARG held meetings restricted to university researchers, a lot of useless debate went on about methods. Managing the process becomes really important, otherwise it's just an academic free-for-all.'

This effort was fundamentally a programme of government agencies, not groupings of academic researchers. Managers, who enjoyed great respect from both field-oriented workers and bench scientists, were chosen primarily for their scientific ability and secondly for their talent as managers. The point of choosing managers on the basis of their scientific stature was mentioned several times by the interviewees: 'These guys could smell bullshit a mile away.' Apart from the talent and influence of the managers, a characteristic element of this programme was its multidisciplinary nature. Biologists, geologists, chemists and physicists were required to work together. Groups within PLUARG reported to the International Joint Commission, a respected neutral third party with no political agenda. This type of overall coordination is necessary to effective management and policy development: the technical challenges involved in eutrophication are at least as complex as those surrounding stresses on modern coral reefs.

Government policy was extremely responsive to research results. Phosphorus-based detergents were banned in Canada before all the evidence was in. The USA acted more slowly, state by state, in the face of opposition from the detergent lobby.

The major findings of the sources and effects of eutrophication in the Great Lakes were largely produced by a couple of dozen key scientists, working over a 10-year period (for example, Ongley 1976). There was a great deal of computer modelling of ecosystem function during this programme. In fact, it was this programme, and the acid-rain programme that followed a decade later, that laid the basis for advanced ecosystem decision support systems that are now in use. The models used in management were much simpler than those used in research: 'simple things work best.'

All elements required for an action plan to be implemented were therefore in place:

— an informed and politically active public;
— political commitment at the national level;
— technically competent managers, responsive to their political masters;
— financial commitment.

North America became the leader in management policy for large lakes (National Academy of Sciences, Anon. 1969). Other countries, now experiencing eutrophication problems in their lakes, have not learned from the lessons of North

America in the 1960s. The reasons for this are unclear. One opinion is: 'A generation of scientists has passed, and the young ones now think they are the first to invent that particular wheel. There is no institutional memory.'

This programme of applied science was a 'success', in that research fed effective policy development. The problem lessened for a time, but development continues to affect the Great Lakes. It now seems that the programme underestimated the importance of long-range atmospheric transport of pollutants and of nitrogen to eutrophication of the Great Lakes..

Acid rain in the Northern Hemisphere

In North America, concerns about acid rain were raised by the sport-fishing industry in the early 1970s. The first reports in the primary literature followed within two years (Beamish and Harvey 1972). Early concerns in Canada centred around changes in fish populations downwind from emissions from the mining industry in Sudbury (at the time, it was not fully understood that acid precipitation travels thousands of kilometres). The first experiments with liming lakes in the Sudbury region were performed in the mid 1970s.

The countries then most affected by acid precipitation were all technically advanced: Canada, which was affected by industries in the north-central USA, and Scandinavia, which received fallout from Europe. The first multinational conference on acid rain was held in 1978, about 5 years after identification of the problem. 'Methodology was always the big battle, pitting biologists against chemists.' It was necessary to establish protocols to allow intercalibration of the various methods: in the end, disagreements over methodology were dealt with by quality assurance programmes and intercalibration exercises.

The progression from first identification of the problem to useful scientific outcomes took less than a decade. The programme was driven by national governments of the concerned countries. The scientific framework was therefore in place to allow adoption of relevant policy. The damage from acid rain, of course, continues. To streamline monitoring techniques to detect acidification, most nations have adopted techniques that emphasize the use of bioindicators.

Summary

These two programmes provided scientific, technical and policy frameworks within which the problems of nutrient input and acid rain may be viewed. Each programme was a scientific success. The elements that contributed to success were as follows.

- These were international programmes, made possible because of commitment at federal levels.
- Managers were chosen, above all, for their technical ability.
- The programmes were truly multidisciplinary.
- Problems of different methodologies were solved by agreement on quality assurance protocols.

Afterword

These scientific and policy successes were temporary. Politics has delayed implementation of many of the recommendations, especially in the USA. In addition, Canada is no longer an environmental world leader. The 1999 Report of the Commissioner of the Environment and Sustainable Development (Office of the Attorney General of Canada 1999) paints a damning picture of declining resources, poor management and departmental infighting. Some selections from this Report are illustrative, because they provide a blueprint of the destruction of a scientific resource, and a warning to other nations:

'Environment Canada's resources for monitoring have been declining steadily since 1990 ... Our audit identified many weaknesses in the federal government's collection and use of scientific information ... We found weaknesses in interdepartmental co-ordination of research efforts, incomplete monitoring networks ... conflicting departmental agendas and priorities, and a growing gap between the demands placed on departments and the availability of resources to meet those demands ... we believe that conflicts between departments have in many cases surpassed a healthy level of debate and have led to strained relations, indecision and inaction, inefficient use of federal resources and expertise and ... Canada's international embarrassment.'

The response of the USA and Canada to an environmental crisis now could not be what it was in the 1960s and 1970s. Critical pieces are missing. Above all, there is now a lack of dedicated, competent scientific management and a lack of leadership and direction from the top. I believe that lack of good management is as fatal as lack of funding.

Dawning realization of the reef crisis

Recognition of some of the major stresses acting on coral reefs occurred more than a century ago: 'the effects of sediment on growing zoophytes are strongly marked, and may be often perceived when a mingling of freshwater alone produces little influence' (Dana 1872). Equally interesting is the antiquity and accuracy of early observations on bioerosion: 'Innumerable boring animals establish themselves into the lifeless stem, piercing holes in all directions ... A still more destructive agent ... are ... minute boring sponges, which penetrate in all directions' (Agassiz 1851).

In a more modern context, the major environmental stresses on coral reefs were identified more than 20 years ago. The effect of sewage, siltation and urban development on the reefs of Hawaii was described by Banner (1974). Endean (1976) outlined a variety of natural and anthropogenic stresses, including sewage, siltation, industrial discharge and destructive fishing methods. Similarly, the most commonly used survey methods for coral reefs (line transects, quadrats, and visual estimates of fish abundance and variety) were described more than 25 years ago (Risk 1972).

The major stressors of coral reefs, therefore, were identified, and the techniques to monitor them, 25 years ago.

By the early to mid 1980s, it was apparent that there was widespread damage to coral reefs as a result of human activities. In the Caribbean, there were changes in the growth rate, community structure and reproduction of corals (Tomascik and Sander 1985, 1987*a*, 1987*b*). In Latin America there was reef modification and extirpation by sediments derived from deforested watersheds (Cortes and Risk 1982, 1985), and on the Great Barrier Reef there was description of the depredations of boring sponges and their response to nutrients (Bergman and Risk 1982). There was widespread public concern; the preliminary results from the sedimentation study in Costa Rica (Cortes and Risk 1985) were incorporated into Costa Rican legislation.

In summary, by the early 1980s, the following elements were in place:
— information on the major factors controlling development of reefs;
— evidence of widespread anthropogenic damage to reefs;
— monitoring and evaluation methods; and
— a concerned public.

Present status of the world's reefs

The world's coral reefs seem to be in decline. Consider the situation in Indonesia, the country with more coral reefs than any other. Tomascik *et al.* (1997) quote a description written by Umbgrove in 1928 of the marine community around the resort island of Leiden (now Nyamuk Besar, 'Big Mosquito'), in Jakarta Bay: 'The unrivaled splendor and wealth of forms and the delicate tints of the coral structures, the brilliant colors of fishes, clams, sea anemones, worms, crabs, star fishes and the whole rest of the reef animals are so attractive and interesting that it seems impossible to give an adequate description of such a profusion of serene and fascinating beauty.' By 1985, the coral cover around the island was down to less than 1% (Scoffin 1986; Tomascik *et al.* 1997). Similar studies of the once-thriving reefs of Jakarta Bay have shown that they are now functionally dead (Tomascik *et al*. 1993). Entire coral islands have disappeared.

Research from other parts of Indonesia paints a similar picture. Edinger *et al.* (1998) report that coral cover and diversity on reefs on Java, Sulawesi and Ambon have been affected by sewage and siltation and are about 50% lower than on nearby comparison reefs. They estimate a decrease in generic diversity of corals of >25% in the past 15 years and state (p. 617) 'The decreased diversity on reefs subject to land-based pollution implies a dramatic, rapid decrease in Indonesian reef-based fisheries resources.'

These sorts of problems occur on reefs throughout the world. Bryant and Burke (1998) present the following:
— 58% of the world's reefs are threatened by human activity;
— 70% of all reefs outside the Pacific are at risk;
— 80% of the reefs of South-East Asia are at risk, as are most reefs in the USA;
— nearly 2/3 of the reefs in the Caribbean are in jeopardy;
— although there are >400 marine parks worldwide that contain coral reefs, most are very small; and
— almost half the countries possessing reefs lack any marine protected areas.

Since most of the elements required to mount effective scientific management programmes were in place about 20 years ago, and since concern about the status of reefs dates from that time (and has recently accelerated dramatically), it is appropriate to investigate what systems are now in place that would allow any nation to identify and ameliorate the stresses affecting its reefs.

Response of the coral reef scientific community to the reef degradation crisis

A literature study based on the journal Coral Reefs

To investigate the degree to which the coral reef scientific community has responded to this crisis, I have abstracted data from *Coral Reefs*, the publication of the International Society for Reef Studies. I have reviewed articles published in that journal since inception in 1982 until mid-1999, searching for those articles I considered to be useful or potentially useful in management of reefs, identification and evaluation of stresses on reefs, and/or rehabilitation of reefs.

The results are given in Fig. 1. Throughout the 1980s and into the early 1990s, research that could readily be used in a monitoring, evaluation and/or stress identification programme was relatively scarce. The amount of published research increased rapidly through the 1990s, reaching a peak in 1994–95. In those years, almost half the papers published annually could be classified as 'useful'. In the past two years, the numbers have dropped. The response of the coral reef scientific community seems to have lagged identification of the problem by at least a decade.

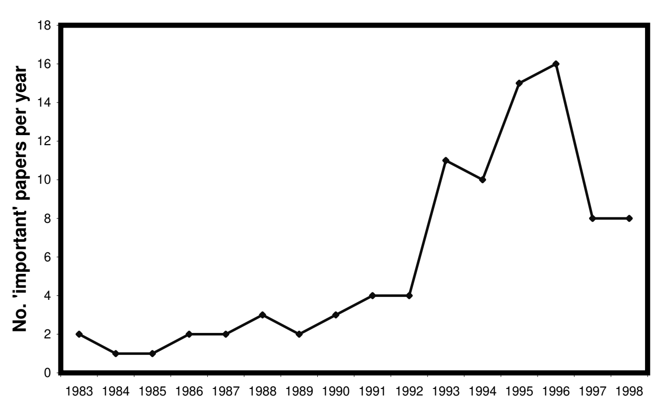

Fig. 1. Proportion of papers published in *Coral Reefs* since inception of the journal deemed to be of relevance to monitoring, evaluating or restoring coral reefs.

Monitoring systems

Line transects, quadrats and visual fish counting were described over 25 years ago (Risk 1972). Done (1977) reported that all the survey techniques he used gave basically the same answer, results that were verified by Chiaponne and Sullivan (1991). Risk and Risk (1997) reported that, for management purposes, survey results need only have a precision of ± 20%, and that efforts to achieve higher precision were 'a waste of time and money' (p. 1472).

Notwithstanding these previous studies, there is no general agreement on a common methodology for monitoring coral reefs, although appropriate methods are available and the problem is far from complex. Indonesia has adopted a national monitoring system with a common methodology, the first nation to do so. Some countries have adopted monitoring protocols: in the USA, there are active monitoring programmes (Wheaton *et al.* 1999) and rapid reef assessment programmes (Miller and Swanson 1999) centred in Florida. One of the most effective international programmes is Reefcheck (Hodgson 1999) which uses volunteer labour and a system of bioindicator species.

One of the largest monitoring programmes is operated by the Australian Institute of Marine Sciences (AIMS) (e.g. Sweatman *et al.* 1998). Like all large monitoring programmes, it is expensive and time-consuming. It is 'designed to detect changes over time in reef communities at a regional scale.' There has been a massive amount of data collected in this programme, which is commendable. On the other hand, as annual surveys are run between September and May, beginning in the north and working south, seasonal changes will be difficult to separate from spatial and temporal changes. It will take perhaps 30–50 years to accumulate enough baseline data to allow useful generalizations to be made. There is no emphasis on bioindicators. This is strange, considering there has been at least a 5-fold increase in sediment and nutrient loading in the area in historic times (Bell and Elmetri 1995). The AIMS programme does not specifically target the characteristic bioindicator and geochemical signals produced by sewage and sediment stress.

Monitoring is not an end in itself. Ideally, monitoring programmes first establish baseline conditions, then feed directly into stress-identification and mitigation programmes. At present, none of the reef-monitoring programmes in place or contemplated are so oriented, with the exception of small efforts in Indonesia using the bioerosion technique described by Holmes (1997). Most environmental monitoring programmes in the developed nations for ecosystems other than coral reefs have abandoned broadbrush techniques and have adopted methods based on bioindicators.

It must be clearly understood that monitoring based upon corals introduces a large time-lag between the process and the response, possibly in the order of five years or more. By the time a monitoring programme based on corals produces indisputable evidence of stress, corals are already dying. There is no doubt that large monitoring programmes are and will continue to be a feature of reef-related activity, and there is equally no doubt that most of them will be colossal wastes of money.

The present situation is that most coral reef monitoring and evaluation is not linked to stress identification. There has been a plethora of international meetings on coral reefs in recent years, with limited results on management policy in reef-possessing nations. In the case of the crises of eutrophication and acid rain in the Great Lakes and Northen Hemisphere, 10 years elapsed between perception of the problem and production of useful policy and management frameworks. After 20 years, reef problems are still in the identification stage, and no useful policy initiatives have been adopted. This, by my definition, constitutes a 'failure' of science, and the reasons for this bear investigation.

Possible reasons for the failure

As was described earlier, successful international efforts to combat environmental problems contain several key elements. In the case of coral reefs, some of these key elements are either lacking or have been de-emphasized.

Interdisciplinarity

The great majority of reef programmes are operated by biologists. A viewpoint that is exclusively biological misses the geological perspective which is the only meaningful way to assess decline in reefs over time. It also misses the importance of chemistry and geochemistry in fingerprinting sources and timing of stresses on reefs. 'Ecology' by definition includes knowledge of all the sciences, and there is no ecosystem more appropriate to the marriage of geology, chemistry and biology than coral reefs. This is a concept more honoured in the breach than the observance.

Geologists have not been as directly involved in monitoring efforts as have biologists, and hence escape much of the criticism in this paper. On the other hand, some reef geologists seem mired in a mindset that sees the present situation in the oceans as just another blip in the stratigraphic column, and the rises in sea level following global warming as merely the Holocene Transgression revisited. Hutton would be appalled by this inability to use the present as a key to the future.

Management

Biology, geology and chemistry have not worked well together in addressing the problems facing modern coral reefs. This lack of coordination stems from a lack of competent management.

One key ingredient in the success of the programmes discussed above was the presence of senior, respected, technically trained managers, who led from the front and not the rear. This ingredient may be presently lacking in reef science, although we have several eloquent spokespersons for reefs.

Reasons for this are not clear, although it may reflect the general late-20th-century trend for 'scientific management' to become the preferred career of persons with backgrounds in areas other than science, or a dumping-ground for those unable to do first-rate science. This may in fact explain the relative success of international development programmes, in particular those involving tropical marine science. SIDA (Swedish International Development Agency) runs technical programmes with technically trained personnel and enjoys both success and respect. CIDA (Canadian International Development Agency) employs no scientists as project managers and enjoys neither consistent success nor widespread respect.

It is not clear how this problem of lack of effective management can be approached; in fact, it will probably prove intractable. Major international funding programmes are not run by scientists, and scientific policies and priorities are generally set by economists; hence, poorly qualified persons will continue to be managers.

Methodology

Rapid, cooperative agreement on methodology or, at least, agreement on the results to be attained, has not been a feature of reef science. No references will be cited here, but almost three decades after Risk (1972) and Done (1977), papers are still published that compare survey methods. This is resumé-padding, not problem resolution. Solution of this situation will come only via effective management.

Commitment

In defence of coral reef biologists, it must be said that governments of the developed nations have been slow to understand the scope of the problem – in fact, much slower than some of the developing nations. Those countries most affected have lacked the resources to mount appropriate programmes.

Makeup and turnover of researchers

Most coral reef researchers are academics, and the best academics are independent, argumentative and (often) fractious. Individual careers may be advanced while agreement on methodology lags. Theoretical science is superbly done by academics, but not so the task of setting up large, integrated programmes.

Summary

The response of the scientific community to the crisis facing coral reefs has been slow in comparison with response times to previous international environmental crises. Twenty years after the first warning signs, and more than 20 years after the first description of survey methods, there is still no detection–identification–remediation protocol in place in any country. Reasons for this seem to include, but not be limited to, the following: lack of truly interdisciplinary programmes, and dominance of the field by one scientific discipline, biology; lack of competent technical management; lack of agreement on methods, and lack of development and adoption of bioindicator-based techniques and geochemical indicators.

Recommendations

(1) All existing and contemplated coral reef monitoring programmes should be abandoned and replaced with community-based bioindicator programmes designed to identify stress. These early-warning indicators should be tied to known geochemical techniques that can fingerprint and date the sources of stress — information that feeds directly into policy, legislation, and management.

(2) Managers of reef monitoring and amelioration programmes must be scientists who command wide respect amongst those responsible for collecting the data.

(3) Reef scientists need to heed the precautionary principle, embodied in Principle 15 of the Rio Declaration: 'Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.'

Predictions

(1) None of the Recommendations stated above will be adopted.

(2) A developing nation will be the first to adopt an effective system of monitoring for stress on reefs, coupled with stress identification techniques, and will be the first to incorporate knowledge so gained into effective legislation. It is amongst developing nations that the problem is felt most keenly, and it is there that scientific turf wars and career- and reputation-building take a back seat to feeding people.

(3) Reefs as some of us knew them will have vanished from much of the inhabited coastlines of the globe by the end of the next decade.

Acknowledgments

I thank those anonymous colleagues who agreed to be interviewed so that I could learn something about the progress of research in Great Lakes eutrophication and acid rain. My appreciation of the need for practical inspection/detection/amelioration systems to deal with the crisis in coral reefs comes from my association with friends, too numerous to mention, living in coastal villages in East Africa, the Caribbean, Central America and South-East Asia. I am saddened by my view of their future. I also owe special thanks to a reviewer, a distinguished colleague who prefers to remain anonymous; his comments were of great help in organizing my impassioned rantings into more or less comprehensible form.

References

Agassiz, L. (1851). Florida Reefs. Coastal Survey Report.

Anon. (1969). 'Eutrophication: Causes, Consequences, Correctives.' (National Academy of Sciences Press: Washington, DC.) 661 pp.

Banner, A. H. (1974). Kaneohe Bay, Hawaii: urban pollution and a coral reef ecosystem. Proceedings of the 2nd. International Coral Reef Symposium, Brisbane **2**, 685–702.

Beamish, R. J., and Harvey, H. H. (1972). Acidification of the LaCloche Mountain Lakes, Ontario and resulting fish mortalities. *Journal of the Fisheries Research Board Canada* **29**, 1131–43.

Bell, P., and Elmetri, I. (1995). Ecological indicators of large-scale eutrophication in the Great-Barrier Reef Lagoon. *Ambio* **24**, 208–15.

Bergman, K. M., and Risk, M. J. (1982). Sediment production and reef framework destruction by a boring sponge: Great Barrier Reef, Australia. Geology Society of America Program 14, Abstract 4.

Bryant, D., and Burke, L. (1998). Reefs at Risk: a map-based indicator of threats to the world's coral reefs. (World Resources Institute: Washington DC.) 56 pp.

Chiappone, M., and Sullivan, K. M. (1991). A comparison of line quadrat transect versus linear percentage sampling for evaluating stony coral (*Scleractinia* and *Milleporina*) community similarity and area coverage on reefs of the central Bahamas. *Coral Reefs* **10**, 139–54.

Cortes, J., and Risk, M. J. (1982). Effect of siltation on a modern coral reef: Parque Nacional Cahuita, Costa Rica. Geology Society of America Program 14, Abstract 12.

Cortes, J., and Risk, M. J. (1985). A reef under siltation stress: Cahuita, Costa Rica. Bulletin of Marine Science **36**, 339–56.

Dana, J. D. (1872). 'Corals and Coral Islands.' (Dodd, Mead: New York.)

Done, T. J. (1977). A comparison of units of cover in ecological classification of coral communities. Proceedings of the 3rd International Coral Reef Symposium, 9–14.

Edinger, E. E., Jompa, J., Limmon, G., Wijdatmoko, W., and Risk, M. J. (1998). Reef degradation and coral biodiversity in Indonesia: effects of land-based pollution, destructive fishing practices and changes over time. *Marine Pollution Bulletin* **36**, 617–30.

Endean, R. (1976). Destruction and recovery of coral reef communities. In 'Biology and Geology of Coral Reefs Vol. 3, Biology 2'. (Eds O. A. Jones and R. Endean.) pp. 215–54. (Academic Press: New York.)

Hodgson, G. (1999). Using Reefcheck to monitor coral reefs. Proceedings of the International Conference on Scientific Aspects of Coral Reef Assessment, Monitoring and Restoration, Fort Lauderdale, Florida, Abstract p. 105.

Holmes, K. E. (1997). Eutrophication and its effects on bioeroding sponge communities. Proceedings of the 8th International Coral Reef Symposium **2**, 1411–16.

Miller, S. L., and Swanson, D. W. (1999). Rapid assessment methods for monitoring marine protected areas in the Florida Keys National Marine Sanctuary: program design and effects of Hurricane George on reefs in the middle and lower Keys. Proceedings of the International Conference on Scientific Aspects of Coral Reef Assessment, Monitoring and Restoration, Fort Lauderdale, Florida, Abstract pp. 139–40.

Office of the Attorney-General, Canada (1999). Report from the Commissioner of the Environment and Sustainable Development.

Ongley, E. D. (1976). Sediment yields and nutrient loadings from Canadian watersheds tributary to Lake Erie: an overview. *Journal of the Fisheries Research Board of Canada* **33**, 471–84.

Risk, M. J. (1972). Fish diversity on a coral reef in the Virgin Islands. Atoll Research Bulletin No. 153, 1–4.

Risk, M. J., and Risk, A. C. (1997). Reef surveys as an aid in management. Proceedings of the 8th International Coral Reef Symposium **2**, 1471–4.

Scoffin, T. P. (1986). Banding in coral skeletons from Pulau Seribu as revealed by X-rays and U/V light values. In 'Human Induced Damage to Coral Reefs: results of a regional UNESCO (COMAR) workshop with advanced training'. (Ed. B. E. Brown.) pp. 126–34. Diponegoro University, Jepara and National Institute of Oceanology, Jakarta, Indonesia. UNESCO Reports in Marine Science No. 40.

Sweatman, H., Bass, D., Cheal, A., Coleman, G., Miller, I., Ninio, R., Osborne, K., Oxley, W., Ryan, D., Thompson, A., and Tomkins, P. (1998). Long-term monitoring of the Great Barrier Reef. (Australian Institute of Marine Science: Townsville.) 303 pp.

Tomascik, T., and Sander, F. (1985). Effects of eutrophication on reef-building corals. I. Growth rate of the reef-building coral *Montastrea annularis*. *Marine Biology* **87**, 143–55.

Tomascik, T., and Sander, F. (1987*a*). Effects of eutrophication on reef-building corals. II. Structure of scleractinian coral communities on fringing reefs, Barbados, West Indies. *Marine Biology* **94**, 53–75.

Tomascik, T., and Sander, F. (1987*b*). Effects of eutrophication on reef-building corals. III. Reproduction of the reef-building coral *Porites porites*. *Marine Biology* **94**, 77–94.

Tomascik, T., Suharsono, A. J., and Mah, A. (1993). Case histories: a historical perspective of the natural and anthropogenic impacts in the Indonesian Archipelago with a focus on the Kepulauan Seribu, Java Sea. In 'Proceedings of the Colloquium and Forum on Global Aspects of Coral Reefs: Health, Hazards and History'. (Comp. R. N. Ginsburg.) pp. J26-J32. (Rosenstiel School of Marine and Atmospheric Sciences, Univ. of Miami.) 420 pp.

Tomascik, T., Mah, A. J., Nontji, A., and Moosa, M. K. (1997). The ecology of the Indonesian Seas, Part 1. (Periplus Editions: Jakarta.)

Wells, S. M. (1988*a*). Coral Reefs of the World. Vol. 1: Atlantic and Eastern Pacific. (UNEP/IUCN.) 373 pp.

Wells, S. M. (1988*b*). Coral Reefs of the World. Vol. 2: Indian Ocean, Red Sea and Gulf. (UNEP/IUCN.) 389 pp.

Wells, S. M. (1988c). Coral Reefs of the World. Vol.3. Central and Western Pacific. (UNEP/IUCN.) 329 pp.

Wheaton, J. L., Jaap, W. C., Dustan, P., and Porter, J. W. (1999). EPA/hardbottom monitoring project, Florida Keys National Marine Sanctuary., Proceedings of the International Conference on Scientific Aspects of Coral Reef Assessment, Monitoring and Restoration, Fort Lauderdale, Florida, Abstract p. 203.

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