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Friday, 13 December 2002

Mr Greg Murtough,
Productivity Commission

Dear Mr Murtough

I am writing to provide comments on the "Draft Research Report for the Industries in the Great Barrrier Reef Marine Catchment …". I congratulate you on a thorough and timely report, and the emphasis placed on the need for a risk management approach. However, I have some real concerns about the perceived extent and strength of the evidence that water quality changes are affecting the reef, as outlined overleaf. I also clarify some of the points based on my papers or my comments on the earlier draft. I hope that you will find the attached comments useful.

Yours sincerely,

Laurence McCook, (Ph.D),
Research Scientist,
Coral Reef Ecology.

# Comments on Productivity Commission Draft Research Report on Industries in the GBR Catchment and Measures to Address Declining Water Quality


## Laurence McCook,

## Coral Reef Ecologist, Australian Institute of Marine Science & CRC: Reef.


### Overall Comments:

Overall, I felt that the Commissioners had done an impressive job of summarizing the range of information available on this issue. I was especially pleased to see the emphasis the Report placed on the need for a risk management approach to the issue.

However, throughout the Key Points, Overview and, to a lesser extent, Chapter 2, I felt that the summaries presented seriously understated the extent and strength of the evidence that changes in runoff are affecting the reef, or, conversely, that the uncertainty inherent in some of this evidence is overstated. As the Commissioners are aware from our previous communications, I am insistent that the uncertainty and incompleteness of the evidence be acknowledged; however, I consider it imperative that this uncertainty can not be taken as either, i. undermining the considerable and strong evidence that degradation is and will continue to result from current runoff levels; or ii. supporting arguments that there is no effect: there is certainly no convincing evidence of any kind that the increased inputs to the reef waters are *not* having any effects. The evidence available is strong, considerable and convincing (below), if not technically conclusive. Conclusive evidence is something to be avoided at all costs, since it will require further degradation of reefs in comparison to present data. Most critically, given the line of evidence I presented in my submission (12, reiterated below), the available evidence indicates that ongoing degradation is *<u>the most likely outcome</u>* of present runoff levels.

This point is perhaps best illustrated by the choice of the word "circumstantial" to describe the evidence, in contrast to "conclusive". Technically, this is appropriate since the only way conclusive proof could be obtained is to allow ongoing degradation, and measure it. However, in the public eye "circumstantial" is used to mean inadequate or unconvincing (in the context of criminal law, as opposed to civil law); I think the tone and choice of words in the report should rather reflect the strength of the available evidence. (In fairness, I must accept some responsibility, as the Commissioners gave me the opportunity to comment on a draft of Chapter 2; in retrospect I was naïve about the significance of choice of words could play in the non-scientific, public arena. However, I also felt there was a significant difference in the strength of presentation between Chapter 2 and the Key Points and Overview).

To reiterate my summary of the evidence:

1. **There is ample and undisputed evidence that the inputs of sediments, nutrients and chemicals such as pesticides to the waters of the GBR have increased considerably.**
   *Note that on this basis alone, given the status of the GBR as a Marine Park and World Heritage Area, we are morally and legally obliged to address the problem, unless it can be <u>proven to be having NO important effects</u>.*

2. **There are *many* experimental studies which demonstrate explicit causality between relevant levels of runoff components and detrimental impacts on critical reef organisms or processes** (detailed summaries and references for peer reviewed publications in international scientific literature given in my original submission, or available on request);

3. **There are alarmingly high numbers of examples, from tropical and temperate ecosystems around the world, of degradation at the ecosystem or community levels being strongly related to runoff, eutrophication and changes in land-use** (similarly, detailed list of scientific publications in my original submission; note also that this evidence requires that the GBR must be demonstrated to be qualitatively different to all these examples if it is to be argued to be safe or immune from the accepted inputs)**;**

4. **There is considerable evidence strongly indicating that those pollutants are currently contributing to decline of inshore coral reef and other habitats on the Great Barrier Reef** (again, detailed list of scientific publications in my original submission)**;**

Importantly, whilst it is true that this does not provide categorical, conclusive proof, and that it is *possible* that uncertainties in each step *might* provide some protection to the reef, it is equally true, and more significant, that **the *<u>most likely</u>* outcome of these circumstances is that the reef is being degraded, and will continue to be seriously degraded without urgent and comprehensive measures to reduce runoff.**

I would like to suggest the relevant parts of the final report should be carefully worded to emphasize this balance of likelihood, and the strength and relevance of the evidence behind it, rather than issues of conclusiveness or circumstantiality.

SPECIFIC COMMENTS ON DRAFT REPORT:

Text quoted from the Draft Report is shown in blue text.

**Key points**

- Water quality in rivers entering the Great Barrier Reef (GBR) lagoon has declined because of land uses in the adjacent catchment. This poses a **<u>significant threat to inshore reefs and associated ecosystems</u>**. True.
- While there is no conclusive evidence yet of water quality decline within the GBR lagoon or of any resulting damage to ecosystems, there is circumstantial evidence.

As outlined above, I think this is a serious understatement of the evidence: there is considerable and strong evidence. Indeed, I would express the sentence the other way around: "There is considerable, strong evidence indicating declining water quality and resulting damage to inshore ecosystems, especially coral reefs, on the GBR, although completely conclusive evidence may not be possible until significant further decline has occurred."

- Because of the World Heritage values that may be at risk, a strategy to identify, prioritise and manage risks is warranted, notwithstanding the considerable scientific uncertainty about the condition of reefs and associated ecosystems.

Again, I think this understates the problem, and the strategy: the WH values *are* at risk; describing the uncertainty as "considerable" appears to suggest that there may not be a problem, which is very unlikely; also the identification, prioritisation and management of risks is important, but I consider that there is an urgent need to address or reduce the risks (further study of the problem must not delay action to reduce runoff, indeed it requires such action in order to begin to provide information on the effectiveness etc of different measures…)

- Point sources of water pollution are already tightly controlled, but the existing regulations are not well-suited to diffuse sources of pollutants (such as sediments, nutrients and chemicals from agriculture and grazing lands).
- Some primary producers have already demonstrated that it is possible and viable to reduce land and water degradation on their own lands, which then improves downstream water quality in rivers and estuaries flowing into the GBR lagoon.
- Policies to encourage greater adoption of such 'Best Management Practices' — particularly in the cattle grazing and sugar cane industries — could be beneficial.
- Better monitoring and more research is an urgent priority in formulating and implementing sound policies to ensure the continued protection of the Great Barrier Reef.

Again, I think the last four points seriously understate the urgency and extent of measures required to address the threats to the GBR; if those measures listed here are all that takes place, there is a real prospect that considerable further degradation will occur. Phrases such as "could be beneficial", "not well suited" etc do not convey the strength and commitment required: the existing regulations are *inadequate*; Policies to *ensure full* adoption….are *needed*, and not just for adoption of *existing* best management practices; and whilst better monitoring and more research are needed to improve the formulation and implementation of sound policies, it is vital that this happen in *parallel* with, not prior to, the implementation of policies to actually address the problem.

### OVERVIEW

<u>p. XXV: Impacts of water quality decline:</u>

- Again, I consider the summary statement to seriously understate the extent and strength of the evidence: based on my 10 years first hand experience, observations and experimental research, and literature review, I consider that "There is considerable, strong evidence indicating declining water quality and resulting damage to inshore ecosystems, especially coral reefs, on the GBR, although completely conclusive evidence may not be possible until significant further decline has occurred."
- The adaptation of inshore reef *corals* to naturally higher sediment and nutrient levels *may* make them more robust, but there is little if any evidence to suggest it makes them more robust to *further increases*, and it may actually mean that the *reef* system as a whole is in fact already stressed, and hence more vulnerable.
- The sentence: "It is possible that conclusive proof that water quality decline has damaged the GBR and associated ecosystems will only become evident after irreversible damage has occurred." is misleading, in my opinion, since, firstly, it is unavoidably the case, not just *possibly* so, and secondly, it will require irreversible damage *in comparison to recent condition*, whether or not reefs are *already* degraded: in other words it requires us to sit by and measure further degradation (and assumes that we have the methodology to do so). This is because the kind of "conclusive proof" demanded will require high quality, quantitative data on reef condition *prior* to the damage, and such data are only available from around the mid-1980's.
- Finally, the summary paragraph for this section (p. XXVI), similarly uses the conclusive - circumstantial terminology, and urges "caution" about activities that lead to pollutant discharge into the GBR lagoon. It is accepted that these

activities *are occurring*, so that caution alone will not be sufficient: there is an urgent need for measures to change those activities to reduce the pollutant discharge.

Water quality and management practices:

- I commend the report's explicit recognition of i. the effort made by individuals within primary industries, and ii. the need to identify good and bad practices within any primary industry, rather than stereotyping entire industries (p. XXVI).
- The statement that "*Some* studies have shown that native woodlands generate higher runoff than cleared areas *with well-maintained* pasture." needs to be very cautiously applied - and referenced, since such statements can be and are applied out of context to justify inappropriate clearing, or to compare native woodlands and overgrazed pastures, etc. I suggest italicizing the "well-maintained", and qualifying: "Some studies have shown that, *in some circumstances*, native woodlands *may* generate higher runoff than well-maintained pasture."
- The section on Other Crops that compares usage and application rates for banana and sugar cropping is ambiguous: usage over the whole catchment (or per acre)?, and application rates per unit area (or time)?

## CHAPTER 2:

Again, I commend the Commissioners on an impressive job of summarising the evidence and issues, but would like to suggest that the evidence for a problem is much stronger than this presentation indicates. As indicated above, I would like to acknowledge the extent to which the report incorporated my previous comments on the draft (and express my regret for not being more meticulous in my review at that time; in retrospect I should have done so, but at the time I was very busy.)

- p. 10: line 6: I would like to suggest that "risk management" be used in place of "precautionary", the latter term often being taken to mean "take no risks" rather than "assess and manage the risks" as is required.
- Section 2.2. first para: the sentence referring to natural cycles in coral reefs seems out of place in this context (since it refers to potential *impacts,* section 2.4). It would be more relevant to say that "Levels of nutrient fractions naturally vary considerably within relatively short distances or times even within a location, especially near reefs where tides, currents, mixing, and biological processes can generate large changes in nutrient and sediment concentrations."
- p. 14: The quote from Miles Furnas needs to be clearly placed in the context of floods, since as given it (& the previous sentence) appears to imply that high levels of pollutants in rivers are often not a problem for the reef: in contrast, even if flow rates are so low that the pollutants are not currently discharged, the vast majority of relevant pollutants *will* ultimately reach the GBR waters, usually in the first flood. Perhaps it could be qualified by modifying the preceding sentence to "Whilse such runoff can have implications for the quality of water in rivers, the consequences for the water quality of the GBR will depend on the amount and nature of discharge from the river."
- p. 19, last paragraph: The suggestion that Hinchinbrook channel receives outflow from the Herbert and Burdekin is misleading: the mouth of the Burdekin is ~ hundreds of km south, and the southern outlet of the Channel is shallow and narrow: the extent of sediment inputs to the channel from Burdekin flood plumes would be minimal. Further, the major outflow of the Herbert during large floods (the intervals of interest here) bursts straight out to sea from the southern end of the channel, with only a small proportion of the plume moving up the channel (pers. obs. and ref. by Wolanski but I don't have specific reference handy). Further the tidal currents in the channel are such that sediments would be very unlikely to accumulate in the channel.

- p.21 1st sentence: need to add the word "suspended" to: "Even where increased sediment export is evident, this does not necessarily mean that suspended sediment concentrations in the GBR lagoon are higher (GBRMPA 2001c)".
- p. 21: I would also like to suggest the indicated changes to the next paragraph: However, terrestrially-derived sediments may not need to persist to have an impact*, since corals may be smothered without sediments persisting in the long-term* (McCook, L., pers. comm., 9 October 2002). ~~Further, McCook (AIMS, sub. 12, p. 10) noted the possibility that the proportion of fine sediment loads has increased, which has consequences for future resuspension, *and for the transport of pollutants such as pesticides and nutrients*.~~ In addition, as noted by GBRMPA (2001c), the ~~content~~ composition of the sediment (in terms of nutrient *and pesticide* loads, for instance) is also important. Further, McCook (AIMS, sub. 12, p. 10) noted the possibility that the proportion of fine sediment loads has increased, which has consequences for future resuspension*, and for the transport of pollutants such as pesticides and nutrients*. On this, McCook (AIMS, sub. 12, p. 10) argued that the synergistic effects of multiple stressors are likely to be more significant than increased sedimentation alone (this is discussed further in section 2.4).
- p. 22 first para. This para could benefit by adding the following sentences:
  "The only truly long-term data for water quality on the GBR stem from comparisons of phytoplankton data collected in 1928-1930 by the British Museum Expedition in the Low Isles with recent measurements (Bell 1991, Bell & Elmetri 1995)[1]. These measurements do indicate substantial increases, but are severely compromised by the lack of replicate measurements at the earlier date (given the large variation in present measurements, it is unclear whether the low measurements in 1928 represent generally low levels, or unusually low measurements for the time). Thus, the only long-term data provide cause for concern, although they are insufficient to prove long-term change."
- p. 22 2nd para.: Could be followed by: "Recent work by Fabricius, McCook and colleagues (McCook pers comm. 13 Dec 02) has shown significantly higher levels of all water quality measures (dissolved inorganic and organic nitrogen and phosphate, particulate nitrogen and phosphorus, chlorophyll a, suspended sediments) in waters off the wet tropics area, with highly disturbed catchments and high runoff, compared to reefs north of Princess Charlotte Bay, with relatively undisturbed, low runoff catchments. Whilst this spatial comparison does not consistitute proof that the differences are human-derived, the authors consider this to be likely, and, as a minimum, it indicates the potential changes that are likely to result from similar differences in time in land-use and runoff."
- p. 22 final para: Suggest the following addition: "On the other hand, it has been suggested that a failure to detect increased nutrient levels may reflect inadequacies with current measurements, combined with the large background variation (McCook, L., pers. comm., 9 October 2002)."
- p. 25: Nonpoint source pollution from land-uses: It is important to note that fertilizer and pesticide runoff can result not just from *excessive* use, but from generally poor management of applications: poor timing, uncalibrated additions, poor placement, inadequate mounding, etc.
- p. 25 last para-p.26 first para: The assessment of 80% by GBRMPA is entirely consistent with the idea that agriculture is not entirely responsible, and it is important to recognize that even partial responsibility is sufficient to justify reductions. I suggest the following qualifications: "GBRMPA (sub. 27, p. 2) argued that land use, mainly agriculture (including grazing), contributes around 80 per cent of the pollution loads to the GBR lagoon, which appears consistent with the estimates in table 2.3. Although Johnstone Shire Council (sub. 20, p. 2) argued that agriculture is

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[1] Bell PRF (1991) Status of eutrophication in the Great Barrier Reef lagoon. Mar. Pollut. Bull. 23:89-93
Bell PRF, Elmetri I (1995) Ecological indicators of large-scale eutrophication in the Great Barrier Reef. Ambio 24:20-215

'being accused of problems for which it may not be entirely responsible' this is not inconsistent with GBRMPA's figure of 80%, and clearly entire responsibility is not necessary to justify remediation. Furnas (2002) noted the difficulty in determining the nature of linkages between disturbed nearshore reefs and adjacent land use, but it is also true, for example, that there has been no plausible alternative source suggested that can account for either the distribution or quantities of pesticides in marine sediments."

**2.4 Impacts of water quality changes on the GBR ecosystem:**

- p. 33 bottom: "There is, however, disagreement about the nature of some of these impacts empirically. McCook (1999), for example, argued that nutrient overloads can contribute to reef degradation *by a variety of processes*, but that specific process of nutrient enhanced algal overgrowth of corals is unlikely unless 'herbivory is unusually or artificially' low (p. 357). He thus concluded that dissolved inorganic nutrient concentrations alone were poor indicators of reef status, but that when herbivores are scarce, the effects of nutrients on algal overgrowth of corals may be dramatic. In the GBR context, this means that inshore reefs, and reef flats in particular, are particularly vulnerable, since i. they have exceptionally low abundance of herbivorous fishes, as well as proximity to nutrient runoff; and ii. fish abundances decrease with water turbidity (Wolanski et al. in press), suggesting that increased runoff may further reduce herbivore abundances."
- p. 34: Suggest adding the following para after the quote from my 1999 paper: "This conclusion is strongly supported by recent computer modeling work by McCook, Wolanski and colleagues (McCook et al. 2001[2], Wolanski et al in press[3]) which shows that the complexity and diversity of potential runoff effects, in combination with oceanographic and climatic data, can result in dramatic changes in the inshore areas at greatest risk. However, these changes would be unlikely to be detected using present monitoring approaches."
- p. 35 Suggest the following changes:
  Williams (2001), however, reported findings of a study that indicated that, between 1985 and 1995, there was no evidence of decreased hard coral cover or changed coral composition, nor of increased algal cover, on the reef slopes of fringing reefs subjected to more than one survey. However, as this study focused on reef slopes, which have the highest abundances of algae-eating herbivorous fishes, this may reflect the ability of the fish to absorb increased algal growth, and may not represent the situation on the reef flats, which have few fish, and are at greater risk from other stresses, such as bleaching (McCook, L., pers. comm., 9 October 2002)).
- Another study of 1995, which compared historical and modern photographs of reef flats exposed at low tide, suggested that, of the 14 locations examined, ~~only~~ four had shown definite deterioration (at least one of which had recently been subjected to cyclones), while four appeared to be subject to partial decline (cited by Williams 2001; McCook, AIMS, sub. 12, p. 7). ~~This indicated a decline in some reefs,~~ Although the authors of the study suggested that it did not imply widespread decline over the whole GBR (see Williams 2001, pp. 35–6) due to the very limited nature of the dataset, it does indicate 25-50% of inshore reefs in good condition 50-100 years ago are now in poor condition

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[2] McCook LJ, Wolanski E, Spagnol S (2001) Modelling and visualizing interactions between natural disturbances and eutrophication as causes of coral reef degradation. In: Wolanski E (Physics biology links in the GBR. CRC Press, Boca Raton, pp 113-125

[3] Wolanski E, Richmond, R., McCook LJ, Sweatman, H. (in press) Mud, marine snow and coral reefs: The survival of coral reefs requires integrated watershed-based management activities and marine conservation. American Scientist.

(McCook subm 12). Importantly, this is the only truly long-term dataset for reef condition, and most or all of the photographs are from the area currently of concern (inshore reefs in areas of most agricultural activity).

- To the extent that declines in coral health have been evident, it is difficult to assess the extent to which this has or has not been the result of a decline in water quality, or other human influences, or natural disturbance. Nonetheless, McCook (AIMS, sub. 12, p. 8) and Furnas et al. (AIMS, sub. 12, p. 9) pointed to recent studies by Fabricius and McCook at AIMS, comparing reef status adjacent to developed areas in the wet tropics and adjacent to undeveloped areas further north. These studies are strongly suggestive of human impacts (see also section 2.3). The reefs adjacent to the developed catchment have low cover and diversity of corals, larger areas covered by algae, and, critically, have relatively low settlement and survival of new corals, suggesting they have little capacity to recover from other disturbances.
- p. 35 final para: Furnas' argument that pesticides etc are likely to outweigh the effects of nutrients and sediments, is likely to underestimate the combined effects, since it implies that the effects are independent (one or the other). It is much more "likely that the different stresses synergize and accentuate each other: seagrasses stressed by herbicide or pesticide chemicals will be less able to address problems of sediment deposition, reduced light for photosynthesis and overgrowth of epiphytes due to the enhanced nutrients."

**2.5 Summing up:**

As previously indicated, I strongly disagree with the balance of assessment in the final two dot points, which appears to support the argument that there is unlikely to be a problem because the evidence for the problem is imperfect. Unfortunately, the lack of conclusive evidence simply reflects the lack of high quality, pre-impact data, not the safety of the reef. If we are lucky, it *may* also reflect minimal impact *so far*, but it is unlikely to indicate that the reef is safe under current practices. A wording that more accurately represents the full extent of the evidence for and against impacts, might be:

"Given the considerable and strong evidence that runoff components are highly detrimental to reef organisms and ecosystems, the numerous examples of extensive degradation from similar causes elsewhere in the world, and the limited but consistent evidence for degradation on the inshore GBR, the most reasonable interpretation is that the runoff is having and will have serious impacts on the GBR, although the evidence is, inevitably, not conclusive."

# Mud, Marine Snow and Coral Reefs

*The survival of coral reefs requires integrated watershed-based management activities and marine conservation*

Eric Wolanski, Robert Richmond, Laurence McCook and Hugh Sweatman

Coral reefs are the most diverse of all marine ecosystems, and they are rivaled in biodiversity by few terrestrial ecosystems. They support people directly and indirectly by building islands and atolls. They protect shorelines from coastal erosion, support fisheries of economic and cultural value, provide diving-related tourism and serve as habitats for organisms that produce natural products of biomedical interest. They are also museums of the planet's natural wealth and places of incredible natural beauty.

Despite their recognized biological, economic and aesthetic value, coral reefs are being destroyed at an alarming rate throughout the world. Some countries have seen 50 percent of their coral reefs destroyed by human activities in the past 15 years. Some human influences are acute—for example, mining reefs for limestone, dumping mine tailings on them, fishing with explosives and cyanide, and land reclamation. Reefs that experience such insults often die; those that deteriorate but survive cannot recover to their original health as long as the disturbances continue. In other countries the disturbances are more chronic than acute. Reefs are assaulted by muddy runoff, nutrients and pesticides from adjacent river catchments, overfishing and global-warming effects. These disturbances affect the key parameters permitting reef resilience: water and substratum quality. As a result, corals fail to reproduce successfully, and the coral larvae arriving from more pristine reefs are unable to settle and thrive on substrata covered by mud, cyanobacteria or fleshy algae. Coral populations thus fail to recover or re-establish themselves.

Can science help save coral reefs? Despite much talk about managing coral reefs, the potential role of science is limited. But it is important: Scientists can demonstrate the key processes controlling the health of coral reefs and how human activities damage them. Then, we can hope, land-use managers and marine-resources managers will be able to modify human behavior to reduce or reverse damage to coral reefs. Toward this end we have developed a large-scale model for illuminating reef degradation and predicting the impact of future human activity.

### The Coral Reef Ecosystem

The ecological functioning of a coral reef relies on the symbiotic association between corals and dinoflagellate algae (zooxanthellae). In this system, the dinoflagellates reside as symbionts within the cells of the coral host; the symbionts take in nutrients and produce metabolites from which the corals derive much of their energy. (Corals construct their hard habitat the way mollusks grow their shells, by accreting calcium carbonate.) The main functional components of a coral reef ecosystem include the hard corals, coralline algae, filamentous and fleshy algae, blue-green algae (cyanobacteria), and a host of invertebrates and fishes. Coralline algae are essential to a healthy reef because they cement reef structures and contain chemicals that induce metamorphosis in coral planula larvae. Filamentous and fleshy algae can be very abundant; indeed, the most telltale sign of a degraded coral reef is the replacement of corals by algae *(Figure 2)*.

Three genera of corals dominate Pacific reefs: *Acropora*, *Porites* and *Pocillopora*. *Acropora* corals are the most spectacular; they are also framework builders, providing habitat for a variety of fishes and other reef organisms. They include the table, elkhorn, staghorn and fast-growing branching species. *Porites* corals include boulder or massive corals. *Pocillopora* corals include both coarsely and finely branching species, widely distributed across the Pacific and into the Red Sea.

Natural disturbances including hurricanes (tropical cyclones or typhoons), river floods (*Figure 4)*, earthquakes and lava flows have affected coral reefs for millions of years; they are typically acute and have short-lived effects. Reef areas away from human influences often recover within a few years if water and substratum quality remain high. Acute, natural disturbances thus help maintain diversity on coral reefs by knocking back dominant species and allowing less competitive species to reestablish themselves.

*Eric Wolanski received his Ph.D. in environmental engineering from the Johns Hopkins University in 1972. He is a leading scientist at the Australian Institute of Marine Science, where he studies tropical coastal oceanography and its biological implications for mangroves and coral reefs. Robert Richmond received his Ph.D. in biology from the State University of New York at Stony Brook in 1983. He is a professor of marine biology at the University of Guam Marine Laboratory. His research interests include sublethal stresses on coral reefs. Laurence McCook received his Ph.D. in biology from Dalhousie University in 1992; he is a research scientist specializing in the ecology of algae and reef degradation at the Australian Institute of Marine Science, working with the Cooperative Research Centre for the Great Barrier Reef World Heritage Area. Hugh Sweatman received his Ph.D. from Macquarie University in 1985; he is a research scientist at the Australian Institute of Marine Science where he leads the long-term reef-monitoring program. Address for Wolanski: AIMS, PMB No. 3, Townsville MC, Qld. 4810, Australia. E-mail: e.wolanksi@aims.gov.au*

**Figure 1. Healthy coral reefs such as this section of Australia's Great Barrier Reef not only are aesthetic treasures but also possess the greatest biodiversity of any aquatic ecosystem. In particular, reefs in which various species of the fast-growing, branching *Acropora* corals dominate provide habitat for a spectacular array of life both large and small. Despite their recognized value, reefs worldwide have been degraded dramatically over the past several decades owing to anthropogenic effects, and little has been done to halt their decline. A large part of the problem has been a lack of tools that would allow land- and marine-resource managers to estimate the relative benefits to reef health of various regulatory actions. The authors have developed a model that permits managers to estimate the effects on reefs of regulating various human activities. (Except where noted, photographs by the authors.)**

The synergistic and cumulative effects of human disturbances superimposed over natural disturbances make recovery less likely and, in some cases, result in stable states dominated by algae.

### Marine Snow

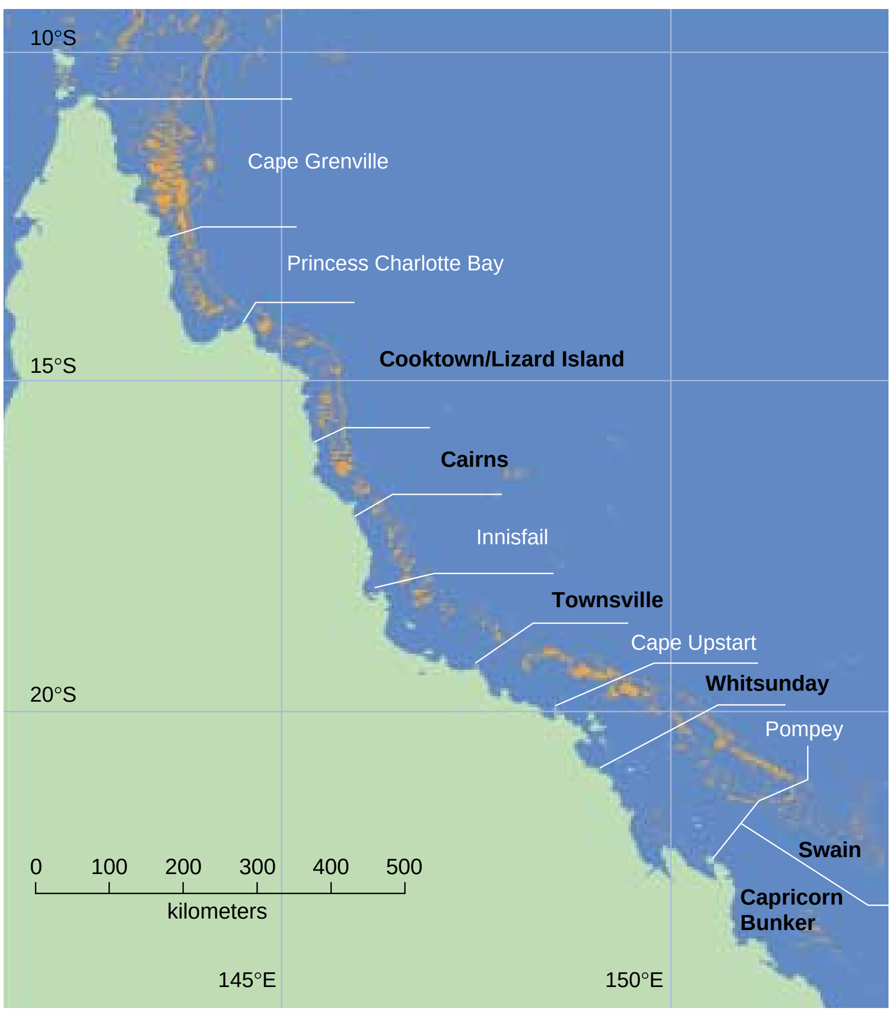
The water around coral reefs sometimes looks clear, but it can contain a variety of suspended matter, starting with inorganic particles such as resuspended calcareous material, fecal material, organic detrital particles, and mucus secreted by plankton, algae and bacteria. Corals themselves secrete mucus to cleanse their colony surfaces and as a metabolic by-product. This mucus prevents corals from becoming clogged with sediment particles and also shields against desiccation if they are exposed to air at low tide. Particles in suspension in water are rapidly aggregated by flocculation as well as by adhesive bridges of exopolymer (mucus). The aggregates resemble snowflakes and hence are called "marine snow" *(Figure 5)*.

Human activities on land often result in increased nutrient concentrations in coastal coral reef waters, which enhances the abundance of algae. In turn, increased nutrients also result in an increased prevalence of marine snow. In the nutrient-enriched coastal waters of Guam and the Great Barrier Reef, marine snow flocs can exceed several centimeters in diameter. Wave-exposed waters have smaller flocs than do more sheltered areas.

Marine snow is almost neutrally buoyant and can remain in suspension for hours in turbulent reef waters. Near-shore waters, however, may contain additional suspended fine clay particles, rich in nutrients and detritus derived from land runoff. This mud in suspension readily attaches to the sticky marine snow, forming muddy marine snow. The clay particles act as ballast that makes the flocs settle onto coral reefs. Muddy marine snow flocs settle fast, typically at a speed of about 5 centimeters per minute—about 1,000 times faster than individual mud particles settle. The settled muddy marine snow has detrimental or even lethal effects on small coral reef organisms.

Corals and reef organisms such as barnacles are able to clean themselves of small settling flocs as long as the silt content remains low—less than 0.5 milligrams per square centimeter. At high siltation levels (4–5 milligrams per square centimeter) or when flocs are large (particles 200–2,000 micrometers in diameter), the coral polyps initially exude thick layers of mucus and die after less than one hour of exposure—a short time compared with the rate of

**Figure 2. Most coral-reef decline, including this example at Palau, is tied in subtle but predictable ways to sediment-laden runoff from human activities within adjacent watersheds. Such runoff may not initiate the decline of a reef; more often, in fact, it prevents a reef from recovering from an acute shock such as a tropical cyclone. The effects are multiple. First, coral larvae, which may have drifted from a distant healthy reef, are unable to colonize because the reef has become covered in a muddy algal mat. Second, those larvae that do establish a foothold may be smothered by newly deposited mud. Third, and at least as significant, the prevalence of herbivorous fish, which feed on the fleshy algae that damage coral larvae, is inversely proportional to water turbidity. In much the same way that regular mowing maintains a fast-growing suburban lawn, herbivorous fish control filamentous algae and enable coral growth. A reef with adult corals but no recruitment of juveniles is in reality dead, but just doesn't know it yet.**




natural marine snow deposition on coral reefs. Katharina Fabricius, at the Australian Institute of Marine Science, found, from laboratory experiments, that settling muddy marine snow flocs are far more hazardous to young than to older corals; the mortality rate is 10 times greater for young coral recruits (newly established animals) than for adult corals. Coral recruits typically die after 43 hours of exposure to muddy marine snow, a threshold that is routinely exceeded in nutrient-enriched coastal waters of the Great Barrier Reef but not in areas farther offshore. The presence of muddy marine snow on coral is often short-lived, resulting from a river flood or from resuspension by wind-generated waves in a storm. The settled muddy marine snow, having done its dirty work, is consumed by plankton and reef organisms, or flushed out by waves and currents. It usually leaves no "smoking gun," just a degraded reef.

Pollutants, including pesticides, heavy metals and hydrocarbons, also degrade coastal reefs. They can interfere with the chemically sensitive processes of reproduction and recruitment in corals and other reef organisms, such as synchronization of spawning, egg-sperm interactions, fertilization, embryological development, larval settlement, larval metamorphosis and acquisition of symbiotic zooxanthellae by young corals following recruitment.

**Figure 3. Model area included 261 reefs in several zones *(black type)* of Australia's Great Barrier Reef. Coral cover on 48 of these reefs has been monitored annually for more than a decade and shows great variability in time and space. This variability is characterized by a major decrease in coral cover following acute disturbances, such as a tropical cyclone or a river flood, and slow recovery thereafter. For instance, tropical cyclone Ivor in 1990 affected the coral cover on all the outer shelf reefs in the Cooktown/Lizard Island sector. Ten years later, the coral had recovered to cover more than 50 percent of the reef surface. Inshore reefs in the Cairns sector recovered slowly after losing coral cover through the combined effects of bleaching, coral-eating crown-of-thorn starfish infestation and tropical cyclone Rona in 1999. Among mid-shelf reefs near Townsville, fast-growing tabulate *Acropora* corals dominate Rib Reef. The reef cover was severely affected by starfish infestation in the 1980s and has failed to recover for a number of reasons, including tropical cyclone Justin in 1997. Coral cover declined sharply on two mid-shelf reefs in the Whitsundays sector in 1997 as a result of tropical cyclone Justin.**

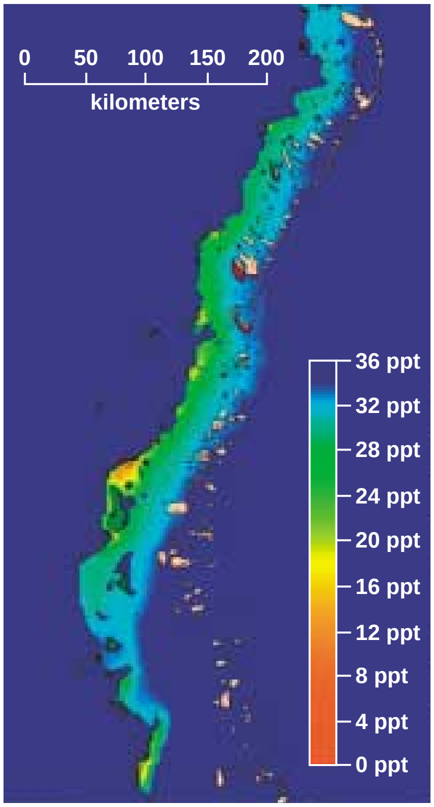



**Figure 4. Muddy plume of the Burdekin River during a river flood, in the Great Barrier Reef near Townsville, can be seen in an oblique aerial photograph. The plume at this location spans 5 kilometers in width and is made readily visible by its high turbidity. Both the entrained mud and reduced salinity can cause acute damage to coral reefs. The map *(above)* shows the salinity distribution in a 400-kilometer-long section of the Great Barrier Reef for the 1991 river flood, predicted by Brian King using a three-dimensional hydrodynamic model. (By contrast, during times of normal river outflow, no reductions in salinity would be evident.) The model uses historical data on daily river discharges, as well as wind speed and direction data, to calculate the movement of river flood plumes from 1969 onwards.**

## The Toll

If, through increased muddiness or pollution, a single link in the coral reproductive chain is broken, the system cascades toward eventual demise. One hundred percent successful fertilization followed by 0 percent recruitment has the same outcome as 100 percent fertilization failure. Therefore many reefs near human population centers simply do not recover from disturbances. Less attractive *Porites* and *Pocillopora* corals replace the habitat-building *Acropora* corals, and, quite often, the benthos becomes covered by fleshy algae, sponges and worms. This in turn causes a shift in resident fish populations. Environmental degradation can also result from overexploitation of populations of herbivorous fishes, such as parrotfish and surgeonfish, which feed on fleshy algae. In overfished systems, fleshy algae can overgrow corals and prevent coral larvae from recruiting.

Human activity will continue to increase. As a result, coral reefs will increasingly degrade—as long as human activities on land and in coral reef waters continue to be managed independently. In both developing countries and developed countries, including Australia, the U.S., Japan and the French overseas territories, different government agencies deal with land-based issues and with marine and reef issues. In Australia, about four agencies deal with land-based issues and two with reefs (not counting fishing). It is as if land and sea were not interconnected ecosystems. This disconnect between watershed-based activities and marine conservation has resulted in serious environmental degradation throughout the world.

Science can help save coral reefs by providing land- and marine-resource managers with accurate and adequate data on keys threats and the synergisms involved, specific indicators of reef resilience, as well as science-based models to predict the impact of vari-

**Figure 5. Marine snow flocs such as the one at left—photographed by Katharina Fabricius in reefal waters of Palau, Micronesia—may reach 30 centimeters in length but are typically smaller—0.5–5 millimeters in size. Flocs are formed by colonies of phytoplankton, fecal pellets, mucus secreted by bacteria and plankton, macroscopic aggregates of *Thalassiosira nana,* large diatoms, dinoflaggelates and tintinnid ciliates, as well as a variety of other plankton and their remains. Additional mucus is produced by diatoms and microbes that colonize the nutrient-rich clay particles derived from erosion in river catchments. Mud readily aggregates on marine snow because it is sticky, forming muddy marine snow flocs, shown spanning 0.8 millimeters in the photograph at right. The mud acts as ballast, forcing the marine snow to settle on the corals, which they smother, particularly the juvenile recruits.**

ous decisions about land use and reef fisheries on reef health. We have developed such a mathematical model for the Great Barrier Reef, for which extensive physical and biological data are available.

## Modeling Reef Health

Australia's Great Barrier Reef stretches along 2,600 kilometers of the east coast of Australia from 25°S to 10°S. The domain of our model comprises 261 reefs in a 400-kilometer-long swath that extends from Lizard Island in the north to the Whitsunday Islands in the south. We wished to model the region believed to be most susceptible to anthropogenic impacts from land runoff *(Figure 4)*. Data to develop the model came from the Long-term Monitoring Program at the Australian Institute of Marine Science, which has surveyed 48 reefs annually since 1992 for assemblages of reef fishes and communities of benthic organisms in the upper northeast reef slope. Reefs for the program were chosen from three shelf positions (inshore, midshelf and outer shelf) at six latitudes, four of which fall within the model domain. Coastal reefs are the most affected by runoff but are not monitored because of poor visibility and the presence of crocodiles. The data on algal and coral cover *(Figures 6 and 9)* present evidence of large changes in the reefs over time in each region; the changes vary among regions. The data show a strong linear relationship between the abundance of herbivorous fish and water visibility *(Figure 7)*—as might be expected, since the fish keep algae populations down—and this observation is central to the formulation of a reef-health model.

The model uses algal cover as a proxy measure of reef health. The ecological components of the model include hard corals in two age groups, juvenile and adult, together with algae and herbivorous fish. Corals and fleshy algae compete for space, and herbivorous fish consume algae. Reef distur-

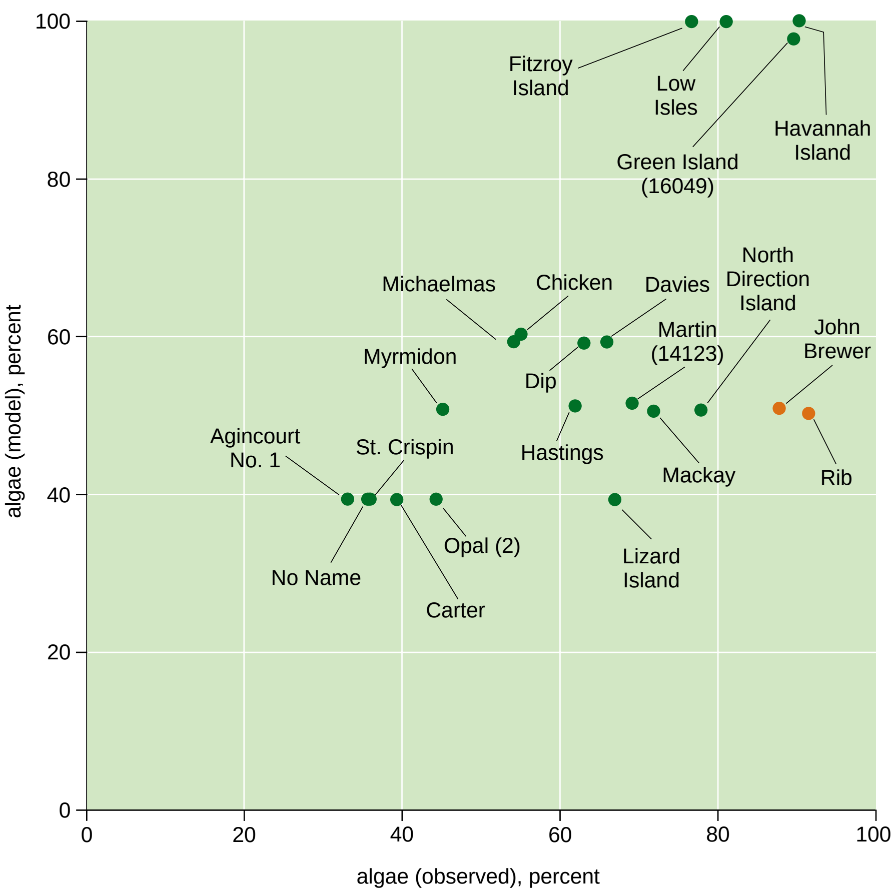



**Figure 6. Algal cover, which displaces corals, serves in the model as a parameter for the health of the Great Barrier Reef. Its distribution has been monitored yearly since 1992 for the 48 reefs. This scatter plot of observed and predicted algal cover suggests that the model has promise. The outlier points *(red)* are reefs infested with the coral-eating crown-of-thorns starfish, *Acanthaster planci*. Such infestations are not incorporated into the model because the ecology of the starfish is insufficiently understood—in particular the ability of the starfish to migrate within a reef and between reefs. Masahra Ogura at Tokai University, Japan, has measured crown-of-thorns starfish migrating at speeds of up to 546 meters per day.**

bances are of two types: acute and chronic. Acute, natural disturbances include river plumes, tropical cyclones and warm-water events resulting in bleaching. These events kill coral, thereby providing free space that is rapidly colonized by filamentous and then fleshy algae. Chronic disturbances come in the form of increased nutrient concentration and the influence of increased turbidity—at least 90 percent of the nutrients from land runoff arrive attached to mud particles. Corals can slowly recover from tissue remnants or through recruitment of larvae from healthier reefs. The recovery rate depends on nutrient concentration and the number of herbivorous fish available to consume algae.

It is not necessary to calculate herbivorous fish dynamics because people do not target herbivorous fish in the Great Barrier Reef; their abundance is predicted by water visibility. It is thus sufficient for the model to set the prevailing visibility conditions from field observations. The mean visibility has apparently halved since 1927—that is, turbidity has doubled—in the Low Isles area near Port Douglas.

Corals spawn each year at night in the early summer, on a date set by the moon phase. In the model, the spawn material is carried by water currents for about 10 days, a conservative estimated time of survival for coral larvae capable of recruitment, by which time most of the coral larvae have left their natal reef. The currents are affected by tides, forcing by the Coral Sea and wind, resulting in connectivity among reefs *(Figure 8)*. Recruitment rates were calculated for every spawning year since 1969, when reliable wind data became available. Outside of spawning periods, coral populations on individual reefs are isolated from each other.

Natural disturbances were determined from historical records of river floods and the trajectory and intensity of tropical cyclones, for which data also are available since 1969. The coral die-off from tropical cyclones was calculated from the trajectory and intensity of the storms, using an empirical function derived from surveys of coral cover immediately before and after the passage of a storm. From models of river plumes, we extracted two key parameters: the minimum salinity and the duration of the river plume at each reef. These parameters in turn were used to calculate the die-off of coral.

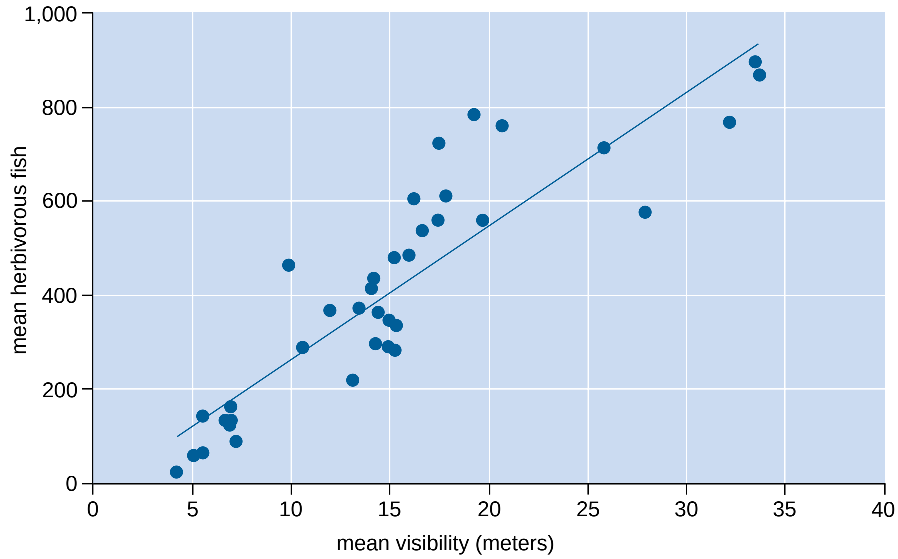



**Figure 7. In Australia's Great Barrier Reef, a relation exists between visibility and the abundance of herbivorous fish. These data were averaged for 10 years of surveys at 48 reefs scattered along a 400-kilometer stretch of the coast. In the model, visibility is used as a proxy for herbivorous fish prevalence.**

The model predicts reef health as parameterized by algal cover in a 400-kilometer-long stretch of the Great Barrier Reef *(Figure 9)*. Without human influences, coastal runoff degrades the reef in a zone whose width and degree of impact vary with latitude, with maximum damage in the Cairns region. Impacts within the zone vary considerably owing to the passage of tropical cyclones; as a result, reefs outside the coastal zone are occasionally covered with algae. The model further predicts that, with human activities on land, the zone of damage has already grown much larger than the natural state and will increase in size and intensity in the future, unless human influences are curtailed. At least as important, the model enables one to quantify the effects of various scenarios for control of land-use activities—anywhere from "do nothing" to "strict control." It offers decision makers and the public a science-based tool to decide what activities should be allowed, and how they should be controlled, on land and at sea, in order to produce a desired state of health for coral reefs. The model could presumably also be used to test the impact on reef health of various levels of fishing for herbivorous fish; this does not apply to Australia's Great Barrier Reef at present, but the question is relevant to most reefs elsewhere in the world, including Micronesia and the

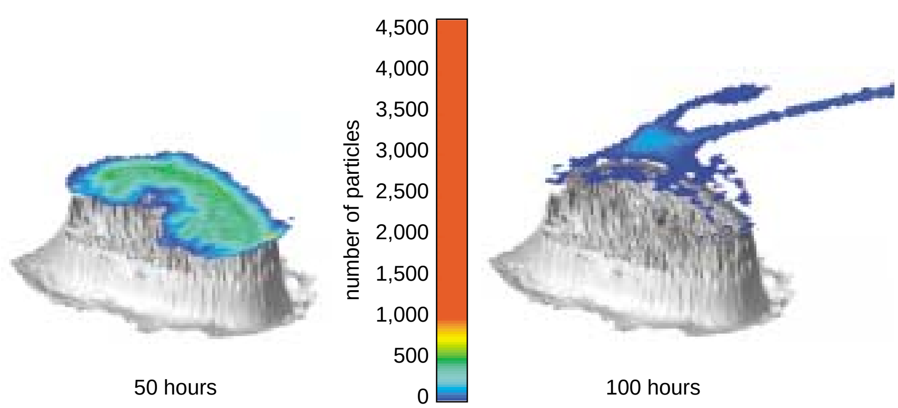



**Figure 8. As visualized from the oceanographic model for Bowden Reef in the Great Barrier Reef, mass spawning of corals creates a plume *(left)* of coral larvae over the reef. This plume slowly mixes and is diluted by ambient oceanic waters while at the same time being carried away by the oceanic currents *(right)*. Larvae from one reef can settle on other reefs. This process enables degraded reefs to recruit coral larvae from healthier reefs. The distribution of source and sink reefs varies yearly with the wind after annual coral spawning.**

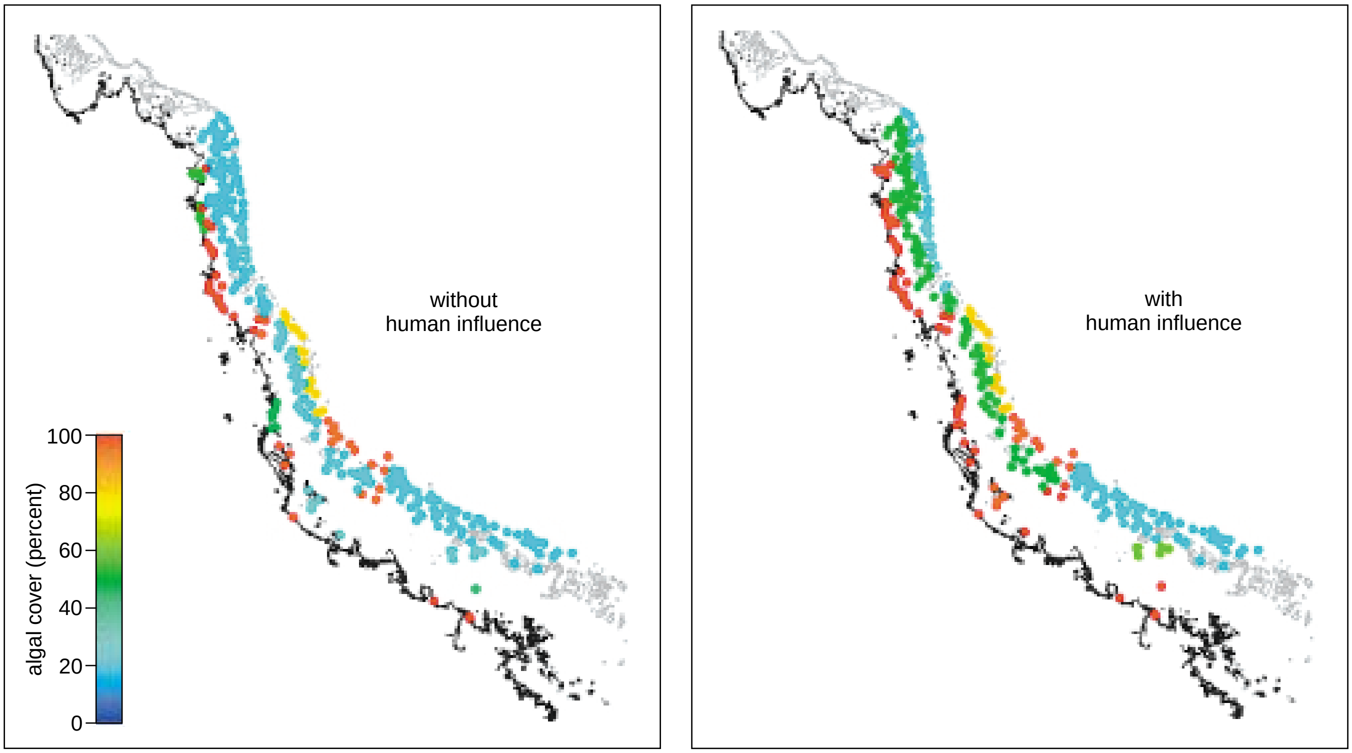



**Figure 9. Model of coral health in this 400-kilometer-long stretch of the Great Barrier Reef was run with and without human influences. The parameter for reef degradation is algal cover. These results suggest that a wide swath is degraded by human activities on land, particularly in near-shore and mid-shelf reefs. The immediate cause of coral death at some sites may be natural, acute disturbances such as hurricanes and river floods. Anthropogenic effects, via land runoff, on water quality appear responsible for the failure of reefs to recover after disturbance. This results in a long-term decline in reef health.**

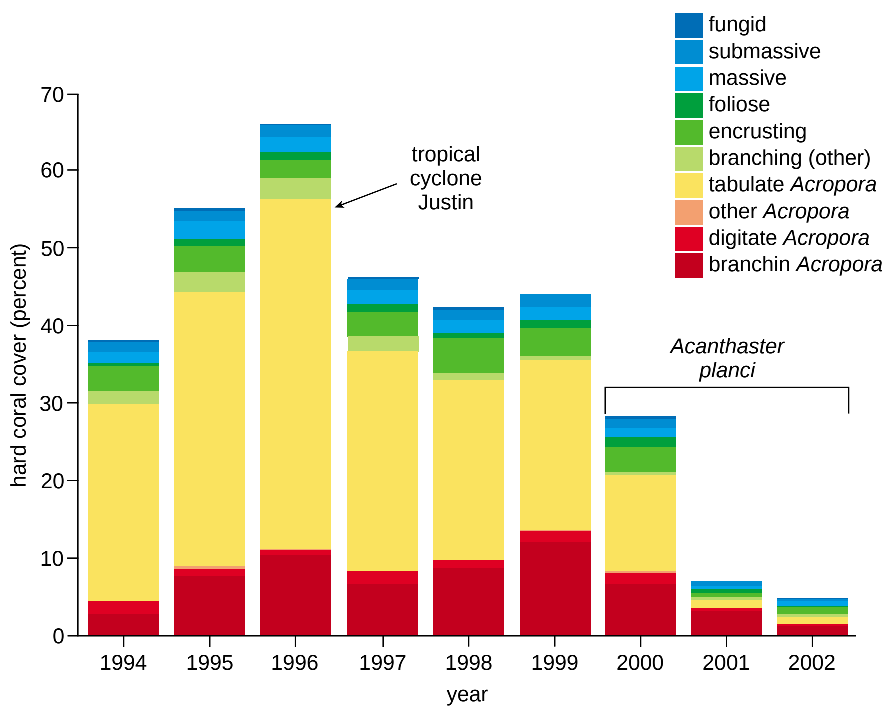



**Figure 10. Annual surveys of hard-corals at Rib Reef on the Great Barrier Reef show the effects of disturbances such as tropical storms and outbreaks of the coral-eating crown-of-thorns starfish, *Acanthaster planci.* Such disturbances have different effects on corals with different growth forms. The horizontal plates of fast-growing table *Acropora* spp. rapidly overgrow other corals but are easily broken during tropical cyclones and are a preferred food for crown-of-thorns starfish. *Porites* corals *(right)* grow slowly, their round shape helps limit storm damage, and their perforate skeleton allows coral tissue to be sequestered during episodes of stress from reduced salinity, sedimentation and eutrophication associated with agricultural runoff and sewer outfalls. After such disturbances, the dead corals are colonized by filamentous or fleshy algae. Algae also replace corals by direct overgrowth. In the photograph, the brown seaweed *Lobophora variegata* is growing up around the branches of *Porites cylindrica,* smothering the coral tissue (shown by the dead, white skeleton where the researchers removed the algae covering the coral tissue).**

U.S. Mariana Islands, where these fish are relentlessly pursued.

**Limitations to Action**

Like all ecosystem models, our model has limitations. These include unknown or poorly understood ecosystem processes, the lack of sufficient data on predisturbance water quality or habitat status, the lack of data from undisturbed sites and inadequacies in the measurement of water-quality parameters. Additional ecological processes could be added to the model, but this does not make it more useful because these new processes require additional parameters for which data are unavailable. Prediction of the response of a reef to human influences is thus inherently uncertain.

Unfortunately, uncertainty in ecosystem models cannot readily be quantified; too often, this is used as an excuse for inactivity, citing that "more research is needed before a sound decision can be made." Rather, the major impediment at this point appears to be political will. Scientists could do much more to exert influence—for example, by translating existing scientific data into the social and economic costs of inaction and making this information available to stakeholders and the broader community. Otherwise, "proof" of impacts will have to wait for serious degradation—and in comparison to current data, rather than the undocumented predisturbance state. Clearly this outcome must be avoided. The objective should be prevention, not demonstration, of extensive degradation. Effective monitoring programs must go beyond documentation of coral reef demise and be used as tools to guide responses that prevent outright mortality.

Examples from Guam and Hawaii show that once a reef has been killed, it cannot be restored, even by importing outside corals, unless the underlying cause—for example, soil erosion in the adjoining catchment—is first addressed. The most logical approach to coral reef restoration is to alleviate those conditions that caused the decline and allow natural recovery to occur. More specifically, restore the water and substratum quality that allows corals and other reef organisms to successfully reproduce and recruit. This means controlling poor land-use practices that spill mud, nutrients and pesticides into coral reef waters; managing fisheries through quotas and fishing-gear restrictions; reducing tourism impacts; and establishing marine protected areas. Science has a crucial role to play in demonstrating the connections between land and reef ecosystems and the profound effects those connections can have.

**Acknowledgements**

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Links to Internet Resources for "Mud, Marine Snow and Coral Reefs" are available on the *American Scientist Web* site:

http://www.americanscientist.org/articles/03articles/wolanski.html


"AND IF THERE ARE ALTERNATE UNIVERSES, THEY AREN'T BIG ENOUGH FOR BOTH OF US."