Watersheds and Coral Reefs: Conservation Science, Policy, and Implementation

ROBERT H. RICHMOND, TEINA RONGO, YIMNANG GOLBUU, STEVEN VICTOR, NOAH IDECHONG, GERRY DAVIS, WILLY KOSTKA, LEINSON NETH, MICHAEL HAMNETT, AND ERIC WOLANSKI

Coral reefs worldwide are being degraded by human-induced disturbances, resulting in ecological, economic, and cultural losses. Runoff and sedimentation are among the greatest threats to the coastal reefs surrounding high islands and adjacent to continental landmasses. Existing scientific data identify the key stressors, synergisms, and outcomes at the coral reef ecosystem, community, and population levels. These data demonstrate that marine protected areas alone may be insufficient for coral reef protection; integrated watershed management practices are also needed. Gaps in the effectiveness of environmental policy, legislation, and regulatory enforcement have resulted in the continued degradation of US and Australian reefs. Several Pacific islands, with intact resource stewardship and traditional leadership systems, have been able to apply research findings to coral reef management policies relatively quickly. Three case histories in Micronesia provide insight into how social sciences and biophysical data can be combined to manage human behaviors responsible for coral reef destruction.

Keywords: coral reefs, watersheds, sedimentation, conservation, traditional knowledge

Coral reefs in the United States and throughout the world are experiencing documented declines in ecosystem health, integrity, and resilience (Wilkinson 2004). While science is an essential element of efforts to reverse this trend, it is insufficient without a means of application through sound policy development and implementation. The presence of multiple stressors often leads to finger-pointing among a variety of users, all defending their own activities while accusing others of culpability; hence, there is a need not only for data that clearly identify cause-and-effect relationships (Downs et al. 2005) but also for improved policy development, implementation, and enforcement. There are sufficient data to address many of the greatest problems facing coral reefs, but policy and political will are lagging behind the available science.

The ability of scientists to affect policy is a timely issue, with ongoing discussions addressing the respective merits of objective data presentation and of advocacy (Lubchenco 1998, Franz 2001). Scientists are often asked to provide input relevant to critical policy decisions; however, in cases such as global warming and cigarette smoking, representatives of industry have also cited "science" to confuse the public, obfuscate the issues, and justify the status quo through what has been called "manufactured uncertainty" (Michaels 2005). In the face of uncertainty, manufactured or real, policymakers often choose inactivity by default rather than subscribe to the precautionary principle. This approach undermines society's ability to leave a sound environmental legacy for future generations.

Robert H. Richmond (e-mail: richmond@hawaii.edu) is a research professor at the Kewalo Marine Laboratory, Pacific Biosciences Research Center, University of Hawaii at Manoa, Honolulu, HI 96813, and a past director of the University of Guam Marine Laboratory. Teina Rongo earned his master's degree in biology at the University of Guam Marine Laboratory in 2005, and is now working as a marine biologist based in the Cook Islands, Avarua, Rarotonga; he has been accepted into the PhD program in the Department of Biological Sciences, Florida Institute of Technology, for the fall semester of 2007. Yimnang Golbuu and Steven Victor are chief researchers at the Palau International Coral Reef Center, Koror, Palau 96940. Noah Idechong is Vice Speaker of the House of Delegates for the 7th Palau National Congress, Koror, Palau 96940; a past director of the Palau Marine Resources Division; and a recipient of the Goldman Environmental Prize. Gerry Davis is the assistant regional administrator for habitat conservation, National Marine Fisheries Service, Pacific Islands Regional Office, Honolulu, HI 96813, and past chief of the Guam Division of Aquatic and Wildlife Resources. Willy Kostka is the director of the Micronesia Conservation Trust, Kolonia, Pohnpei 96941, Federated States of Micronesia, and past director of the Conservation Society of Pohnpei. Leinson Neth is a biologist with the Conservation Society of Pohnpei, Kolonia, Pohnpei 96941, Federated States of Micronesia. Michael Hamnett is the executive director of the Research Corporation of the University of Hawaii and the past director of the Social Sciences Research Institute, University of Hawaii at Manoa, Honolulu, HI 96822. Eric Wolanski is a leading scientist at the Australian Institute of Marine Science, Townsville, Queensland 4811, Australia. Richmond, Idechong, and Kostka are Pew Fellows in Marine Conservation; Richmond was also an Aldo Leopold Leadership Fellow in 2004; and Rongo, Golbuu, Victor, Idechong, Kostka, and Neth are indigenous Pacific islanders experienced in traditional and modern resource management practices.

There is a broad consensus that coral reefs throughout the world have been and continue to be degraded by a variety of human activities (Hughes et al. 2003, Pandolfi et al. 2003, 2005). Runoff, sedimentation, and land-based sources of pollution within adjacent watersheds are among the greatest threats to coastal coral reefs surrounding high islands and along continental margins. While there are numerous efforts under way to address coral reef decline, few positive examples exist that document efforts where science, policy, and management have intersected successfully to reverse the present trend. Numerous reefs in US waters, including those off the coasts of Florida, Puerto Rico, Hawaii, and Guam, have been affected by watershed discharges (Wilkinson 2004). Australia is notable among nations for having one of the most proactive marine zoning systems to regulate marine activities that affect the Great Barrier Reef, as well as for having a single coordinating regulatory body (the Great Barrier Reef Marine Park Authority), but even these protective measures do not adequately manage watershed-based activities, and recent observations and data support models predicting the continued decline of Australia's nearshore and offshore reefs (Wolanski and Dea'th 2005, CSIRO 2007).

Several important efforts are under way, both within the United States and elsewhere, to address the protection of coral reefs and related resources. The reauthorization of the Coral Reef Conservation Act of 2000 is in committee in the US Congress, the US Coral Reef Task Force established by Executive Order 13089 is approaching its 10-year anniversary with a review of past accomplishments and future directions being performed, an International Year of the Reef is being planned in conjunction with the 11th International Coral Reef Symposium in 2008, and the Secretariat for the International Coral Reef Initiative will be shared between the United States and Mexico from July 2007 through June 2009. All of these activities are helping to promote scientific research, community outreach, and education, and to identify financial, institutional, and human resources that can be directed to coral reef protection. Yet public policy still fails to reflect the available science, existing legislation is largely ineffective, and coral reefs continue to decline.

In several Pacific islands, where many coral reefs are still intact but are threatened by development and cultural Westernization, recent research has supported the development of effective policies and implementation strategies for protecting the reefs. We selected three Pacific islands—Guam, Palau, and Pohnpei—as sites for studying how watershed discharges affect coastal coral reefs and how the data can be applied to addressing the problems of multiple stressors. In these case studies, policy development and implementation have been assisted by culturally connected individuals who have helped translate science into policy through their understanding of the sociopolitical landscape, and by communities whose members look to longer-term issues affecting their own and their children's future quality of life. The purpose of this article is to examine elements that lead to success in these three case histories and to discuss how different approaches can be used to improve the US and international responses to coral reef decline.

Watersheds and the land–sea connection

For coral reefs around islands, there are only short distances between the land-based sources of stress and the reefs themselves, and generally the substances used on land (e.g., agrochemicals, petroleum products, and other pollutants) will end up in the coastal zone, either through surface runoff or through aquifer discharge. Fresh water alone is a stressor for coral reefs, and even natural levels of runoff can significantly affect species distribution, reproductive success, and larval survivorship (Richmond 1997). A variety of pollutants can be transported as soluble products or adhere to the surfaces of sediment particles, only to be released upon contact with seawater or with lipid-rich corals. Sediment carried in runoff can also affect corals and reef structure through light attenuation, with subsequent reductions in the photosynthetic contributions of zooxanthellae and increases in energetic costs due to sediment shedding, as well as through outright burial and interference with critical chemical and textural cues responsible for larval recruitment (Rogers 1990, Richmond 1993). More subtle effects include the nucleation of marine snow (Wolanski et al. 2004) and the smothering of benthic infaunal organisms responsible for bioturbation and aeration of sediments, leading to anoxia and to the production of toxic sulfides that can be released during storms and associated wave events (Fabricius and Wolanski 2000, Fabricius et al. 2003). The retention of sediments on reefs, caused by a fleshy and filamentous algal cover, and the subsequent resuspension of accumulated particles result in a lethal legacy (figure 1).

The Western approach to coral reef management

The United States attempts to manage impacts to coral reefs through legislation and regulations, some of which date back over a century and are simply ineffective in protecting living resources (table 1). The Rivers and Harbors Act of 1899, for example, placed the ultimate permitting authority for construction activities on coral reefs under the jurisdiction of the US Army Corps of Engineers. This was presumably done when the government considered coral reefs as primarily hazards to navigation. While the exceptional ecological, economic, and cultural value of reefs has been increasingly recognized, the Corps can still approve permits for activities damaging to reefs over the objections of more biologically oriented agencies, including the US Fish and Wildlife Service, the National Marine Fisheries Service, and the Environmental Protection Agency. With this authority, the Corps continues to carry out stream channelization projects that result in extensive watershed impacts to coastal marine resources.

The National Environmental Policy Act of 1969 also has serious flaws. Although this legislation contains a defined process for environmental review by both regulatory agencies and the public, it has proved ineffective in protecting coral reefs. The language covering environmental impact statements allows for serious conflicts of interest, as environ-

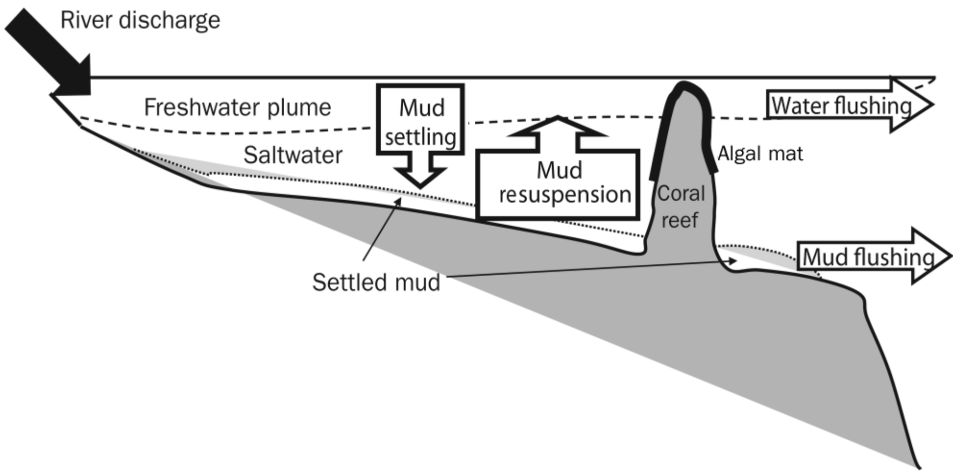

Figure 1. Sketch of the processes affecting coastal coral reefs. The river runoff plumes spread at the surface over the lagoon and are flushed out to the ocean. The transported mud falls out of suspension to form a settled layer that can be either uncompacted (a nepheloid layer) or compacted. This mud is occasionally resuspended by storms and swell, where the bathymetry permits. Fleshy and filamentous algae can overgrow the coral and benthic substrata to form a mat that traps mud and prevents coral recruitment. At low light levels (at times of high turbidity and at night), biological oxygen demand can result in an anoxic bottom layer. The algae typically are grazed by herbivorous fishes; overfishing can lead to a phase shift to algal domination. The retention time of mud is affected by the characteristics of the receiving water, including wave energy and tidal exchange; it is usually much longer than that of the freshwater runoff. Mangroves help shelter the coastal coral reefs by trapping and removing a fraction of the riverine inflow of mud.

mental consultants are usually hired and paid by the individuals who wish to develop or otherwise alter a natural habitat, creating a financial relationship that undermines objectivity. Rarely are coastal marine monitoring programs required of projects that have impacts on adjacent watersheds, and studies serving as the basis for key agency decisions often are incomplete or statistically flawed, or they suffer from falsification by omission. Findings of "no significant impact," a regulatory determination with legal force in the United States, are often scientifically inaccurate conclusions based on insufficient data, poor statistical design, or both. The Magnuson-Stevens Fishery Conservation and Management Act of 1996 (reauthorized in 2006), which affects coral reefs through the fisheries management councils, authorizes management based on demographic analyses of single species rather than the ecosystem-based management approach recommended by the Pew Oceans Commission (2003) and the US Commission on Ocean Policy (2004). Furthermore, definitions, guidelines, and tools for ecosystem-based management strategies are still lacking even when the latter approach is proposed.

Nowhere does US federal legislation explicitly state that it is illegal to kill corals or damage coral reefs. Rather, various laws require mitigation measures of dubious value (e.g., the ubiquitous sediment screens that often fail; figure 2) and only tangentially address parameters such as water quality, applying chemical metrics or biological end points that often were developed in rivers, lakes, or temperate coastal marine ecosystems. Furthermore, accepted model organisms (e.g., *Tilapia* or sea urchins) at a single life history stage do not effectively reflect coral reef responses to pollutants and other stressors across other important taxa or at higher levels of ecological interactions. While there are statutory mechanisms and processes for developing standards specific to coral reefs, these have yet to be applied federally at the level needed to protect reef resources adequately. This is especially problematic when multiple pollutants or stressors are involved in coral reef decline, which is usually the case (Hughes and Connell 1999).

The role of socially responsible science in coral reef protection includes providing accurate and adequate data as well as analytical tools relevant for developing appropriate management policies to reduce human impacts on reef ecosystem health and resilience. However, the legal framework summarized in table 1 documents a major disconnect between the available scientific data and public policy. Since the issue is how to address human behavior rather than coral behavior, a key problem has been the notable absence of the social sciences as part of the solution, leaving the task of coral reef management to biologists and physical scientists who are usually ill prepared to deal with social problems. The integration of the social, biological, and physical sciences is critical to policy development and implementation, and has resulted in several notable, albeit modest, successes within Micronesia, which are largely attributable to the cultural landscape.

Traditional coral reef management systems in Micronesia

The cultures of many Pacific islands have centuries, as opposed to decades, of experience in conserving the coral reefs and other natural resources on which their populations depend. Unlike many Western approaches, the traditional policies in these cultures reflect an understanding that it is not the coral reefs and associated resources that can be managed, but rather the human activities affecting these ecosystems.

In some of these islands, there is still direct reef tenure or ownership, and hence individuals take responsibility for the state of their coral reefs and the fisheries they support. This is different from the "tragedy of the commons" observed in the United States, wherein all have shared ownership, but

Table 1. US legislation of relevance to coral reefs.

Date	Title	Main focus/issue	Main limitations
1899	Rivers and Harbors Act (33 U.S.C. 403)	The US Army Corps of Engineers is authorized to regulate the construction of any structure or work within navigable waters (*http://library.law.unc.edu/ocean-coastal/rha.html*).	The act continues to treat coral reefs essentially as hazards to navigation, and an agency with engineering expertise can override government biologists.
1958	Fish and Wildlife Coordination Act (16 U.S.C. §§ 661–667e, 10 March 1934, as amended 1946, 1958, 1978, and 1995)	"The Act provides that whenever the waters or channel of a body of water are modified by a department or agency of the U.S., the department or agency first shall consult with the U.S. Fish and Wildlife Service" (*http://ipl.unm.edu/cwl/fedbook/fwca.html*).	Coordination and consultation do not necessarily provide a legal framework for conflict resolution when costs to a large segment of the population are greater than the benefits enjoyed by a few.
1969	National Environmental Policy Act (Pub. L. 91-190, 42 U.S.C. 4321–4347, 1 January 1970, as amended by Pub. L. 94-52 [3 July 1975], Pub. L. 94-83 [9 August 1975], and Pub. L. 97-258, § 4(b) [13 September 1982]; *www.nepa.gov/nepa/regs/nepa/nepaeqia.htm*)	"The purposes of this Act are: To declare a national policy which will encourage productive and enjoyable harmony between man and his environment; to promote efforts which will prevent or eliminate damage to the environment and biosphere and stimulate the health and welfare of man..." (42 U.S.C. § 1421).	Most existing standards are chemically rather than biologically based for individual pollutants and ignore the synergistic effects of multiple stressors (i.e., individual levels can be met for lead, copper, and hydrocarbons, but the "soup" is still deadly). The environmental impact assessment/environmental impact statement system is flawed, creating clear conflicts of interest between developers, consultants, and the objective studies needed by regulatory agencies and stakeholders.
1970	Council on Environmental Quality (sec. 201 [42 U.S.C. §§ 4341–4347 and 4372–4375] under NEPA; *www.nepa.gov/nepa/regs/nepa/nepaeqia.htm*)	"NEPA assigns CEQ [Council on Environmental Quality] the task of ensuring that federal agencies meet their obligations under the Act... [and] the challenge of harmonizing our economic, environmental and social [concerns]..." (*www.whitehouse.gov/ceq/aboutceq.html*).	The council operates under the direction of the president, and can change the effectiveness of critical environmental legislation through altering regulations rather than through the legislative process, hence, without public hearings and scrutiny.
1972	Coastal Zone Management Act, as amended through Pub. L. 104-150, Coastal Zone Protection Act of 1996	"This Act establishes an extensive federal grant program within the Department of Commerce to encourage coastal states to develop and implement coastal zone management programs" (*http://ipl.unm.edu/cwl/fedbook/czma.html*).	Coastal zone management programs, while critical elements for the states, commonwealths, and territories with jurisdiction over coastal reefs, often lack the legal force to prevent damage, especially where local laws and political will are weak.
1973	Endangered Species Act, as amended through 1988 (16 U.S.C. 1531–1544)	The Endangered Species Act is "an Act to provide for the conservation of endangered and threatened species of fish, wildlife, and plants, and for other purposes" (*http://thomas.loc.gov/cgi-bin/cpquery/?&sid=cp105IRlXM&refer=&r_n=sr128.105&db_id=105&item=&sel=TOC_192460&*).	Only a few relevant coral reef species, and no coral reef ecosystems, are potentially affected by this legislation.
1977	Clean Water Act (33 U.S.C. §§ 1251–1387, 18 October 1972, as amended 1973–1983, 1987, 1988, 1990–1992, 1994, 1995, and 1996; *http://ipl.unm.edu/cwl/fedbook/fwpca.html*)	"The Act established the basic structure for regulating discharges of pollutants into the waters of the United States. It gave EPA the authority to implement pollution control programs such as setting wastewater standards for industry" (*www.epa.gov/r5water/cwa.htm*).	Present standards are not specific to coral reefs and are chemically based; the regulation of discharges is often simply the permitting of such point and nonpoint sources; legislation is still ineffective for most coral reef communities.
1980	Comprehensive Environmental Response, Compensation, and Liability Act (title 42, chapter 103; *www.access.gpo.gov/uscode/title42/chapter103_.html*)	Also known as Superfund, this law "created a tax on the chemical and petroleum industries and provided broad federal authority to respond directly to releases or threatened releases of hazardous substances that may endanger public health or the environment" (*www.epa.gov/brownfields/other_bf_related_laws.htm*).	To date, this act has had limited application to coral reefs.
1996	Magnuson-Stevens Fishery Conservation and Management Act (Pub. L. 94-265, as amended through 11 October 1996; H.R. 5946, the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act of 2006, was passed by Congress in December 2006 and approved by the executive branch in January 2007; *www.nmfs.noaa.gov/sfa/magact/*)	An act to provide for the conservation and management of the fisheries, and for other purposes.	Actions based on the demographics of single species rather than on ecosystem-based management, with the latter recognized as critical by the US Commission on Ocean Policy and the Pew Oceans Commission; data upon which actions are based are often unreliable or incorrectly assume virgin stock baselines.
1998	Executive Order 13089 on Coral Reef Protection (*www.mms.gov/eppd/compliance/13089/13089.txt*)	Enabling legislation for the US Coral Reef Task Force.	Provides an excellent opportunity for federal and local partnerships, but member federal agencies have conflicting interests and levels of commitment; does not have the legal mandate to prevent activities that may damage coral reefs.
2000	Executive Order 13158 on Marine Protected Areas (*www.nepa.gov/nepa/regs/eos/eo13158.html*)	To establish a national network of marine protected areas.	Marine protected areas remain a critical tool for protecting coral reef resources; however, this legislation may not be able to control extrinsic factors responsible for coral reef losses (e.g., nonpoint source pollution within adjacent watersheds).

Table 1. (continued)

Date	Title	Main focus/issue	Main limitations
2000	Coral Reef Conservation Act of 2000 (Pub. L. 106-562, 16 U.S.C. 6401 et seq. [23 December 2000]; *www.coris.noaa.gov/activities/actionstrategy/08_cons_act.pdf*)	Primarily a funding source for coral reef conservation projects.	This legislation provides funding but not a framework for regulatory activities.
1975	Convention on International Trade of Endangered Species of Wild Fauna and Flora (international convention; United States is a signatory)	Addresses international trade in corals.	US federal and local laws restrict collection of live corals within US jurisdictions, but the United States remains the largest importer of corals from the reefs of other nations.

few take responsibility (Hardin 1968), and there is often a lack of concern among those living upstream regarding the impacts of their activities on individuals and ecosystems further downstream. In numerous Pacific islands, the same villages or clans own both the upland areas and the coastal reefs affected by land-use practices within these watersheds. In addition, many Pacific island cultures treat the land–sea interface as a continuum rather than a boundary, and this "ridge-to-reef" stewardship recognizes that upslope activities affect people and resources farther down a watershed and in the ocean. Pacific island communities with intact reef tenure systems often act to protect their assets through internal governance. Finally, traditional leadership, which still exists in many of these islands, is hereditary, with time horizons longer than the two- to four-year electoral cycles prevalent in Western democracies. This helps to prevent a problem, common in industrialized nations, in which stakeholders and policymakers neglect to consider the future ecological, social, and economic consequences of their present activities on natural resources. Traditional leaders often focus more on legacy issues than on solely short-term financial, professional, or personal rewards, and often ask about the implications of activities for their children and grandchildren.

It is important to recognize that traditional systems of resource management are not always successful. Several recent studies of traditionally based management systems and efforts have identified problems and failures as well as successes in the Pacific and elsewhere (Macintyre and Foale 2004, Cinner et al. 2005a, 2005b). Yet there are elements of traditional systems that lend themselves to the goal and practice of sustainability, and problems often arise in these cultures during periods of transition and under the pressure of outside influences—including the change to a cash economy.

Three Micronesian watersheds and their adjacent coral reefs

Over the past six years, we have studied linkages between watersheds and adjacent coral reefs on three different Micronesian islands—Palau, Guam, and Pohnpei—each with a comparable set of biophysical characteristics but unique cultural attributes (Golbuu et al. 2003, Victor et al. 2004, 2006, Wolanski et al. 2004). The overall study was aimed at identifying the biological and physical parameters affecting the coral reef communities, as well as the social aspects of policy development and implementation within the adjacent human communities. At all three sites, local communities were involved in determining the project scope and design, the study, and the application of research results.

In Palau, we studied Airai Bay, which is bordered by a substantial mangrove forest and is affected by sedimentation from upland clearing for a road, farms, and a housing development. The buffering mangroves, which were found to reduce the sediment load reaching the bay by approximately

Figure 2. (a) An ineffective silt curtain. Developers usually obey rules requiring them to implement mitigation measures. These rules, however, usually do not state that the mitigation measures must be effective or that the developments and watershed alterations cannot result in the death of corals affected by discharges. Photograph: Eric Wolanski. (b) Mangrove forest in the Airai watershed, Palau, being filled for house sites. Silt screens in this area were ineffective and could not replace the buffering value of the mangroves and the associated bacterial and filter-feeding fauna. After data presentations and discussions among researchers, fishers, and local leaders, a moratorium was enacted to prevent any additional filling and destruction of this mangrove forest. Photograph: Robert H. Richmond.

30 percent (Victor et al. 2004), were being cut and filled to make room for houses (figure 2b). The impact of this activity was immediately evident, as the area of coral mortality spread 150 meters farther into the bay soon after the mangrove clearing and the watershed study commenced.

In Guam, we chose Fouha Bay as the research site. It is surrounded by steep hills that deer and pig hunters often burn to clear vegetation, which accelerates erosion rates. The mayor and community members were proactive in requesting that research be performed in their village, and provided guidance and logistical support. The data revealed high rates of sedimentation tied to runoff from rain events (figures 3a, 4), high levels of mud resuspension induced by oceanic swell in the absence of additional rainfall (figures 3b, 4), and high levels of sediment retention in algal mats smothering the coral reefs and preventing the recruitment of coral larvae. Using moving window analysis (figure 5; West and Van Woesik 2001, Rongo 2005), we found statistically significant effects of distance from the mouth of the La Fu Sa River on coral community composition, extending over the entire 300-meter-long bay. Furthermore, transect data taken along the southern side of the bay in 1978 and again in 2003 showed a clear loss of coral species and cover over time that was apparently due to the influence of watershed discharges (table 2; Randall and Birkeland 1978, Rongo 2005). Riverine sediment input in 2003 was found to exceed sediment flushing by a factor of two, on an annual basis (Wolanski et al. 2004).

In Pohnpei, we selected the Enipein watershed for study. It has characteristics similar to those of the Palau site, with an established offshore marine protected area (MPA). The key concern within this watershed is the clearing of the upland rainforest to plant sakau (a narcotizing plant and major cash crop), which has resulted in extensive erosion and subsequent sedimentation of the mangrove-fringed estuary and the coral reefs (Victor et al. 2006). The sedimentation data demonstrated that the coral reef community within the designated MPA was being affected by the watershed discharges, reducing the value of the marine conservation effort. In addition to the environmental damage, several people died in mud slides attributed to forest clearing.

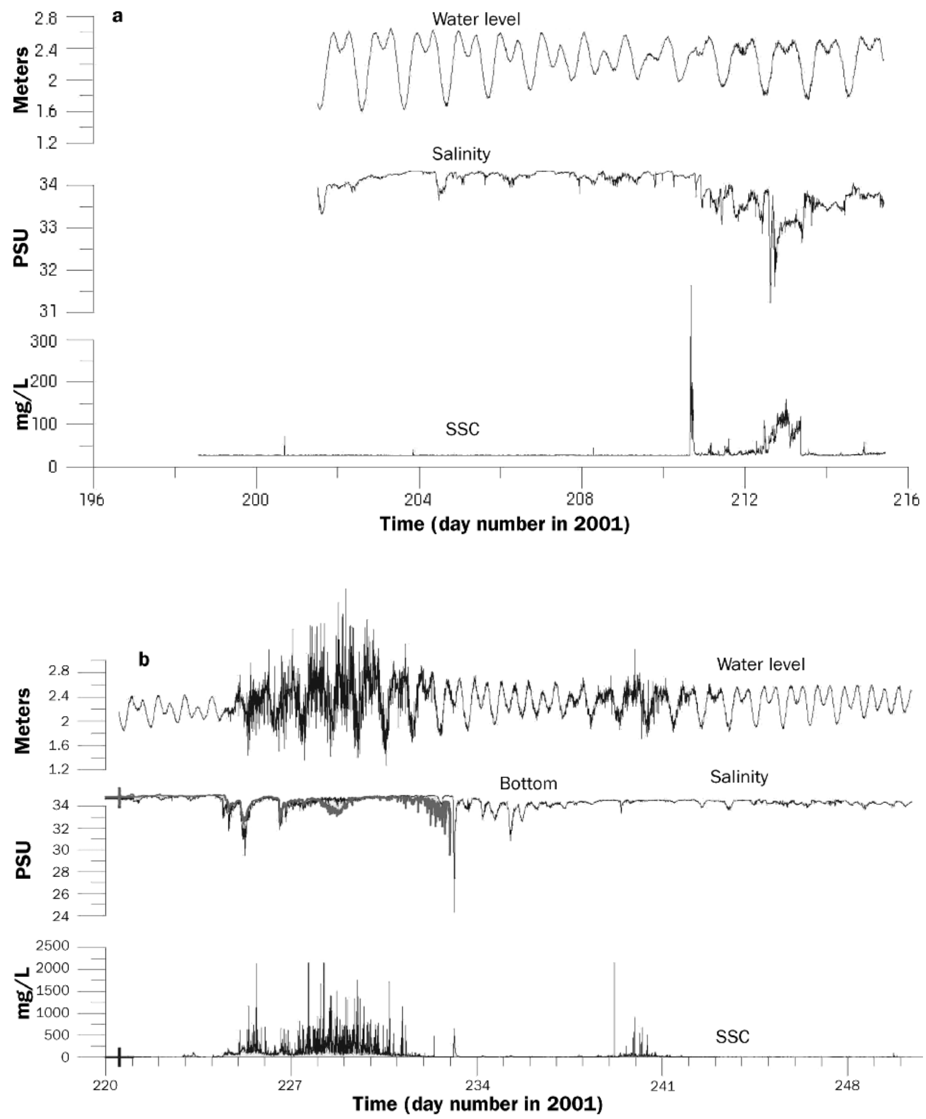

Figure 3. Time series plot of depth (in meters), salinity (in practical salinity units), and suspended sediment concentration (SSC, in milligrams per liter) next to a coral reef in Fouha Bay, Guam, during (a) a river flood in calm weather and (b) the passage of an oceanic swell–generating tropical storm offshore. (a) In calm weather, the river plume directly deposited riverine mud on the coral. (b) The tropical storm brought up mud from the bottom as a result of swell-induced resuspension; the coral was highly stressed by a week of living in complete darkness because of the extremely high turbidity (i.e., SSC was about four times higher than in calm weather under a river plume). After the storm, the salinity at the top and the bottom of the water column was the same as a result of wave-induced mixing. The resuspended sediment had been deposited in the bay during previous floods, demonstrating the legacy effect of earlier, poor land-use practices in the adjacent watershed.

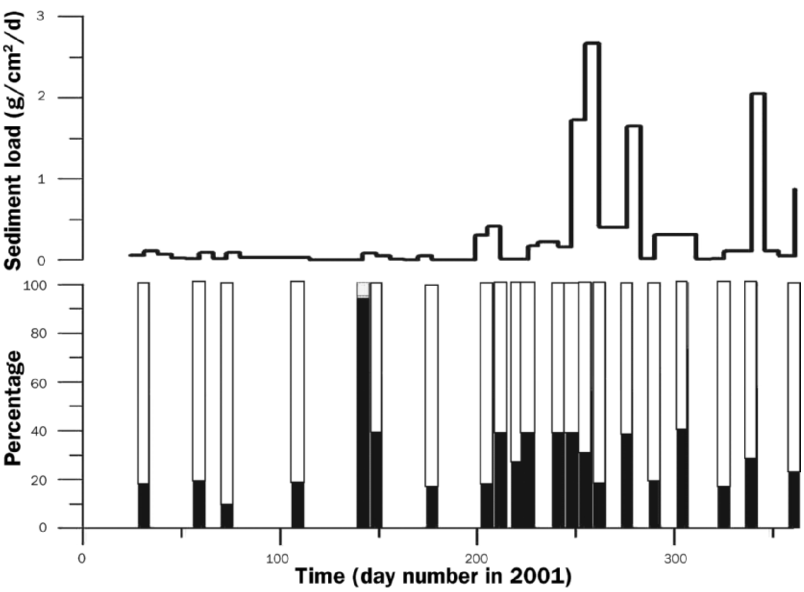

Figure 4. Time series plot over one year of (top) the weekly load of mud deposited over a coral reef in Fouha Bay, Guam, and (bottom) the fraction of that load due to direct riverine runoff (white) and to oceanic swell resuspending the bottom mud (shaded). Adapted from Rongo (2005).

Table 2. Relationship between coral diversity and distance from shore in Fouha Bay, Guam, in 1978 and 2003.

1978		2003	
Distance from shore (meters, cumulative)	Coral diversity (number of species)	Distance from shore (meters)	Coral diversity (number of species)
0–75	40	45–90	5
0–125	89	100–275	41
0–200	104		

at other sites around the island, providing precedence for additional targeted efforts.

In Palau, following presentations at a traditional village meeting by Palauan researchers from the Palau International Coral Reef Center and the staff of the Palau Conservation Society, traditional leaders and fishers worked with the state legislature and governor to stop the leasing, clearing, and grading of the mangroves. This moratorium, initiated approximately six weeks after the village meeting, has now been in effect for over four years in the absence of any formal legislation, and national legislation for watershed protection is now pending before the Palau National Congress. The villagers have worked with governmental and nongovernmental institutions to restore areas within the watershed, and this experience has served as a model for other Palauan communities facing similar problems with their coastal resources.

In Pohnpei, the Conservation Society of Pohnpei used the data from the Enipein watershed research project to convince local chiefs to agree to a continuous protected area that begins in the upland rainforest and extends through the mangroves and out to the reef. Efforts to switch from upland sakau farming to lowland cultivation have been successful, as have been measures to reduce erosion and to protect coastal mangroves. Water and substratum quality are being monitored in the offshore MPA, along

Three outcomes in Micronesia

At all three sites, we identified specific problems tied to human activities responsible for sedimentation effects on the reefs, and recommended a set of scientifically based approaches to each community for reversing the negative trends in reef health.

In Guam, the most Westernized island, the local community worked to restore vegetation within the watershed. Community members also expressed their willingness to work to stop the fires and to support a temporary ban on catching herbivorous fishes within the affected bay, to see if benthic algal cover, and hence sediment retention, could be reduced. After six years, overall progress is occurring. Watershed restoration activities have taken place, as have efforts to enhance community awareness and erosion control. Some burning still occurs, however, and the local community has not yet asked the Guam legislature to establish a marine managed area in Fouha Bay in which the take of herbivorous fishes is controlled. Five no-take areas have been established

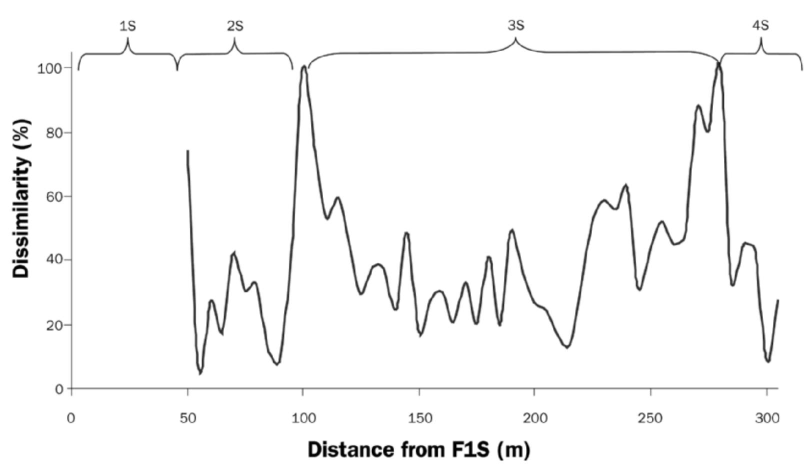

Figure 5. Moving window analysis of coral community structure along a 300-meter (m) transect in Fouha Bay, Guam (see West and Van Woesik [2001] for details of the moving window analysis applied to coral community structure). A 1-m² square frame was tossed at random every 5 m along the transect. Data were recorded from 60 quadrats. F1S is the innermost station along the southern edge of the bay. Each bracketed zone is statistically different in community composition from the others.

with fish abundance, size distribution, and diversity, to determine whether mitigation efforts are proving effective.

In all three cases, communities took ownership of and responsibility for the problems and alternative solutions. Local leaders requested candid and complete analyses of the data from the researchers, but clarified that they did not need others to make value judgments on questions of right and wrong, as these are decisions made within their own cultural context. Such decisions by traditional leaders in Palau and Pohnpei have the weight of legislation, but can be implemented and enforced far more rapidly than can laws in the United States. Compliance with leaders' decisions is also a distinguishing feature of these tradition-based island social systems.

Societal settings and policy

The initial outcome of policy development and implementation efforts was that the islands with intact traditional leadership and ownership of resources were able to quickly and effectively apply scientific data (some of which simply validated what stakeholders already knew) by providing a foundation for discussion and action. This occurred absent the compromise-based approach prevalent in most political settings. The successes came about through the participation of culturally connected researchers, traditional leaders, and community-based organizations rather than through government agencies and national legislation. This bottom-up approach has likewise been successful in other jurisdictions and is used as a model for resource stewardship in many island nations.

Although the United States and other Western countries have a clear edge in technology and data availability, the lack of effective legislation, enforcement, political will, and extensive community-based support remains problematic for long-term environmental stewardship. Cultural systems within some of the Pacific islands provide examples of how to move from data collection to application, which could benefit US policy efforts. Recognizing that traditional resource management systems did not have to cope with many present problems, including a range of chemicals from organophosphate pesticides to toxic antifouling paints, it is clear that a marriage of modern and traditional approaches provides the greatest opportunity to ensure a legacy of robust coral reefs for future generations to enjoy. Although the scale of human impacts on the reefs of Florida is quite different from the magnitude of the problems experienced in Micronesia, the lessons learned are still applicable. Ownership, legacy, stewardship, and responsibility are essential elements of the Pacific islands' approach. Traditional approaches were, and still are, effective in managing human impacts on coral reefs and related resources in Palau (Johannes 1981, 1997), and model legislation (Palau's Marine Protection Act of 1994) was based on this traditional knowledge for protecting specific spawning sites and establishing fisheries closures. If governments can grant coastal and offshore leases for fish cages and oil drilling, why not grant them for community-based conservation, resource protection, and stewardship?

A key role of science in this set of studies was providing technical and ecological knowledge in a form and format that were both accessible and culturally acceptable to stakeholders and local decisionmakers. Notably, stakeholders contributed their traditional ecological knowledge (now recognized and abbreviated TEK by government agencies and conservation organizations) to the reef conservation efforts, which helped provide additional historical and social context for policy development and implementation. Defining the roles of the individual researchers, managers, community leaders, and stakeholders was an important element in this effort to translate science into action. Those individuals with excellent analytical skills were not necessarily the most effective in communicating results. The incorporation of community-based (nongovernmental) organizations was an essential element of stakeholder engagement.

Empowering communities and regulatory agencies by providing them with access to objective academic expertise from public and private institutions of higher education, ostensibly free of political influence, is important. However, financial, liability, and tenure considerations may serve to deter even the most conservation-minded university-based research faculty from becoming engaged in the process of environmental review, discussion, and policy development. This is an issue that needs to be addressed within academia if educational institutions are to be of maximum value to the broader community. Contributions toward scientifically based policy outcomes should be considered in the tenure and promotion process along with peer-reviewed publications and symposium presentations. Academic freedom is essential to meaningful scientific contributions to applied conservation efforts, and is an important asset for researchers confronting the perceived and real scientific censorship that has been experienced at both the federal and the local levels of government.

The main US coral reef ecosystems—in the states of Hawaii, Florida, and Texas; the commonwealths of the Northern Mariana Islands and Puerto Rico; and the territories of American Samoa, Guam, and the US Virgin Islands—have all suffered substantial degradation from land-based sources of pollution and sediment stress. Development within watersheds, the channelization of streams for flood control projects, and other poor land-use practices have turned coastal waters into dumping grounds for runoff, and thus for substances ranging from nutrients to toxic chemicals. Such chronic stressors of increasing magnitude act synergistically when superimposed over natural cycles of coral reef disturbance, and often prevent cycles of recovery that would occur in the absence of the anthropogenic signal.

Even Australia, where the Great Barrier Reef is a national icon, has comparable problems. The socioeconomic imperatives of farmers and developers at the local scale dictate that proactive measures do not in practice extend into watersheds. In 2004, the state of Queensland (with jurisdiction over the land and coastal waters), the Commonwealth's Great

Barrier Reef Marine Park Authority (with jurisdiction over the reef), and local stakeholders collaborated to initiate a 10-year plan with targets and timelines for the reduction of sediment and nutrient inputs from all river catchments adjoining the 2000-kilometer length of the Great Barrier Reef. In practice, however, the implementation of remedial measures has been negligible, because the plan does not provide financial incentives to induce farmers, developers, and municipalities to change their practices. Satellite images taken in February 2007, after a period of heavy rains, found watershed discharges traveling as far as 65 to 130 kilometers offshore to the outer areas of the Great Barrier Reef (CSIRO 2007). This observation hit the mainstream media in Australia as a surprising and high-profile issue. In such instances, science and data are not the limiting factors for improved coral reef conservation practices; rather, policy and implementation are lacking.

Conclusions

Outcomes from the Micronesian programs support the following recommendations for policy development. Coral reefs and other coastal marine ecosystems effectively extend into adjacent watersheds, and should be managed as an integrated unit. Marine protected areas often will miss their targets of resource protection unless coupled terrestrial protected areas (TPAs) are established and enforced. Simply put, TPAs combined with MPAs create effective resource protection areas.

Accumulated sediment is a lethal legacy for coastal coral reefs undergoing phase shifts due to nutrient input and the overfishing of grazing herbivorous species. These sediments are often resuspended by waves, preventing larval recruitment and thus the recovery of affected populations. Sediments also serve as a repository of pollutants as well as sulfides associated with anoxic bottom sediments. Until these issues are integrated into efforts at coastal reef protection, further declines in resources will continue to occur.

The lack of explicit legislative definitions for coral, coral reefs, and coral reef ecosystems limits the capacity of environmental legislation to support needed conservation efforts. Likewise, the vagueness with which community input is collected, weighed, and applied has often reduced the value of public hearings and commentary until they amount to futile formalities. Effective protection will require a comprehensive review of US federal legislation, regulatory agency jurisdiction, and human and financial resource allocation, with stakeholders, researchers, social scientists, and policymakers providing input to help identify roles, opportunities, responsibilities, and accountability.

In light of recent media coverage of environmental issues in the United States, including the debate over global warming, it is important that government scientists be free of interference from their politically appointed supervisors and be allowed to express their true scientific opinions rather than have their reports censored or revised by individuals with potentially conflicted agendas and without the proper scientific credentials. The Union of Concerned Scientists (*www.ucsusa.org*), the National Coalition Against Censorship (*www.ncac.org/science*), and Defend Science (*www.defendscience.org*) have Web sites with detailed and engaging discussions of this issue. Although it is understood that policy decisions need to integrate economic, social, and scientific information within a political context, accuracy of information is critical to the process. In all three cases within the Pacific islands included in this study, community leaders wanted truthful data presentation and candor from the researchers, recognizing that good decisions could not be made in the absence of sound scientific information.

The history of environmental remediation, from cleaning up polluted Superfund sites to addressing harmful algal blooms associated with anthropogenic eutrophication of coastal waters, demonstrates that prevention of environmental degradation is more cost- and time-effective to society than remediation after the fact. While coral reef restoration activities are conceptually attractive, proactive and protective measures are essential, given the magnitude of coral reef damage, the complexity of coral reef ecological structure and function, and the fact that a 300-year-old coral can be killed in hours to weeks, but cannot be replaced for centuries (Richmond 2005).

Finally, formal training designed to improve communications among policymakers, social scientists, natural scientists, and stakeholders is critical to sound policy development and implementation and should be added to curricula across disciplines. Programs such as the Aldo Leopold Leadership Program (*www.leopoldleadership.org*), the Communication Partnership for Science and the Sea (*www.compassonline.org*), and SeaWeb (*www.seaweb.org*) are models that can help train present and future generations of scientists to deal more effectively with the challenges of environmental stewardship.

Acknowledgments

Research funding for this article was provided by NOAA/CSCOR/CRES grant no. NA16OP2920, the US EPA STAR program, and a Pew Marine Conservation Fellowship, a program of the Pew Institute for Ocean Science. The opinions expressed here do not necessarily reflect the opinions of the funding agencies or their representatives. The authors gratefully acknowledge Michael Hadfield, Gary Ostrander, James Maragos, and Charles Birkeland for useful discussions of the material presented in this article, and the communities and leaders of Umatac Village in Guam, Airai Village in Palau, and Enipein Village in Pohnpei for their participation, guidance, intellectual contributions, and goodwill.

References cited

Cinner J, Marnane M, Clark T, McClanahan T, Ben J, Yamuna R. 2005a. Trade, tenure, and tradition: Influence of sociocultural factors on resource use in Melanesia. Conservation Biology 19: 1469–1477.

Cinner J, Marnane M, McClanahan T. 2005b. Conservation and community benefits from traditional coral reef management at Ahus Island, Papua New Guinea. Conservation Biology 19: 1714–1723.

[CSIRO] Commonwealth Scientific and Research Organisation. 2007. Imagery shows outer Great Barrier Reef at risk from river plumes.

Science Daily. 9 March. (13 May 2007; *www.sciencedaily.com/releases/2007/02/070227105400.htm*)
Downs C, Woodley CM, Richmond RH, Lanning LL, Owen R. 2005. Shifting the paradigm of coral-reef "health" assessment. Marine Pollution Bulletin 51: 486–494.
Fabricius K, Wolanski E. 2000. Rapid smothering of coral reef organisms by muddy marine snow. Estuarine, Coastal and Shelf Science 50: 115–120.
Fabricius K, Wild C, Wolanski E, Abele D. 2003. Effects of transparent exopolymer particles and muddy terrigenous sediments on the survival of hard coral recruits. Estuarine, Coastal and Shelf Science 56: 613–621.
Franz EH. 2001. Ecology, values, and policy. BioScience 51: 469–474.
Golbuu Y, Victor S, Wolanski E, Richmond RH. 2003. Trapping of fine sediment in a semi-enclosed bay, Palau, Micronesia. Estuarine, Coastal and Shelf Science 57: 941–949.
Hardin G. 1968. The tragedy of the commons. Science 162: 1243–1248.
Hughes TP, Connell J. 1999. Multiple stressors on coral reefs: A long-term perspective. Limnology and Oceanography 44: 932–940.
Hughes TP, et al. 2003. Climate change, human impacts, and the resilience of coral reefs. Science 301: 929–933.
Johannes RE. 1981. Words of the Lagoon: Fishing and Marine Lore in the Palau District of Micronesia. Berkeley: University of California Press.
———. 1997. Traditional coral-reef fisheries management. Pages 380–385 in Birkeland CE, ed. Life and Death of Coral Reefs. New York: Chapman and Hall.
Lubchenco J. 1998. Entering the century of the environment: A new social contract for science. Science 279: 491–497.
Macintyre M, Foale S. 2004. Global imperatives and local desires: Competing economic and environmental interests in Melanesian communities. Pages 149–164 in Lockwood V, ed. Globalization and Culture Change in the Pacific Islands. Upper Saddle River (NJ): Pearson Education.
Michaels D. 2005. Doubt is their product. Scientific American 292: 96–101.
Pandolfi JM, et al. 2003. Global trajectories of the long-term decline of coral reef ecosystems. Science 301: 955–958.
———. 2005. Are coral reefs on the slippery slope to slime? Science 307: 1725–1726.
Pew Oceans Commission. 2003. America's Living Oceans: Charting a Course for Sea Change. Arlington (VA): Pew Oceans Commission.
Randall RH, Birkeland CE. 1978. Guam's Reefs and Beaches, part 2: Sedimentation Studies at Fouha Bay and Ylig Bay. Mangilao: University of Guam Marine Laboratory. Technical Report no. 47.
Richmond RH. 1993. Coral reefs: Present problems and future concerns resulting from anthropogenic disturbance. American Zoologist 33: 524–536.
———. 1997. Reproduction and recruitment in corals: Critical links in the persistence of reefs. Pages 175–197 in Birkeland CE, ed. Life and Death of Coral Reefs. New York: Chapman and Hall.
———. 2005. Recovering populations and restoring ecosystems: Restoration of coral reefs and related marine communities. Pages 393–409 in Norse EA, Crowder LB, eds. Marine Conservation Biology: The Science of Maintaining the Sea's Biodiversity. Washington (DC):Island Press.
Rogers C. 1990. Responses of coral reefs and reef organisms to sedimentation. Marine Ecology Progress Series 62: 185–202.
Rongo T. 2005. Coral community change along a sediment gradient in Fouha Bay, Guam. Master's thesis, University of Guam, Mangilao.
US Commission on Ocean Policy. 2004. An Ocean Blueprint for the 21st Century: Final Report. Springfield (VA): US Department of Commerce Technology Administration, National Technical Information Service.
Victor S, Golbuu Y, Wolanski E, Richmond RH. 2004. Fine sediment trapping in two mangrove-fringed estuaries exposed to contrasting land use intensity in Palau, Micronesia. Wetlands Ecology and Management 12: 277–283.
Victor S, Neth L, Golbuu Y, Wolanski E, Richmond RH. 2006. Sedimentation in mangroves and coral reefs in a wet tropical island, Pohnpei, Micronesia. Estuarine, Coastal and Shelf Science 66: 409–416.
West K, Van Woesik R. 2001. Spatial and temporal variance of river discharge on Okinawa (Japan): Inferring the temporal impact on adjacent coral reefs. Marine Pollution Bulletin 42: 864–872.
Wilkinson C. 2004. Status of Coral Reefs of the World: 2004, vols. 1 and 2. Townsville (Australia): Australian Institute of Marine Science.
Wolanski E, Dea'th G. 2005. Predicting the present and future human impacts on the Great Barrier Reef. Estuarine, Coastal and Shelf Science 64: 504–508.
Wolanski E, Richmond RH, McCook L. 2004. A model of the effects of land-based human activities on the health of coral reefs in the Great Barrier Reef and in Fouha Bay, Guam, Micronesia. Journal of Marine Systems 46: 133–144.

doi:10.1641/B570710
Include this information when citing this material.