ISRS BRIEFING PAPER 3

THE EFFECTS OF TERRESTRIAL RUNOFF OF SEDIMENTS, NUTRIENTS AND OTHER POLLUTANTS ON CORAL REEFS[1]

SYNOPSIS

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

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

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

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LINKS BETWEEN LAND AND SEA

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

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

WATER QUALITY EFFECTS ON CORAL POPULATIONS

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

Sedimentation

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

Turbidity

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

Goldberg 1995). Consequently, the depth range within which corals can survive or maintain active reef growth diminishes (Yentsch *et al.* 2002).

Nutrients

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

Other pollutants

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

WATER QUALITY EFFECTS ON THE WIDER CORAL REEF ECOSYSTEM

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

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

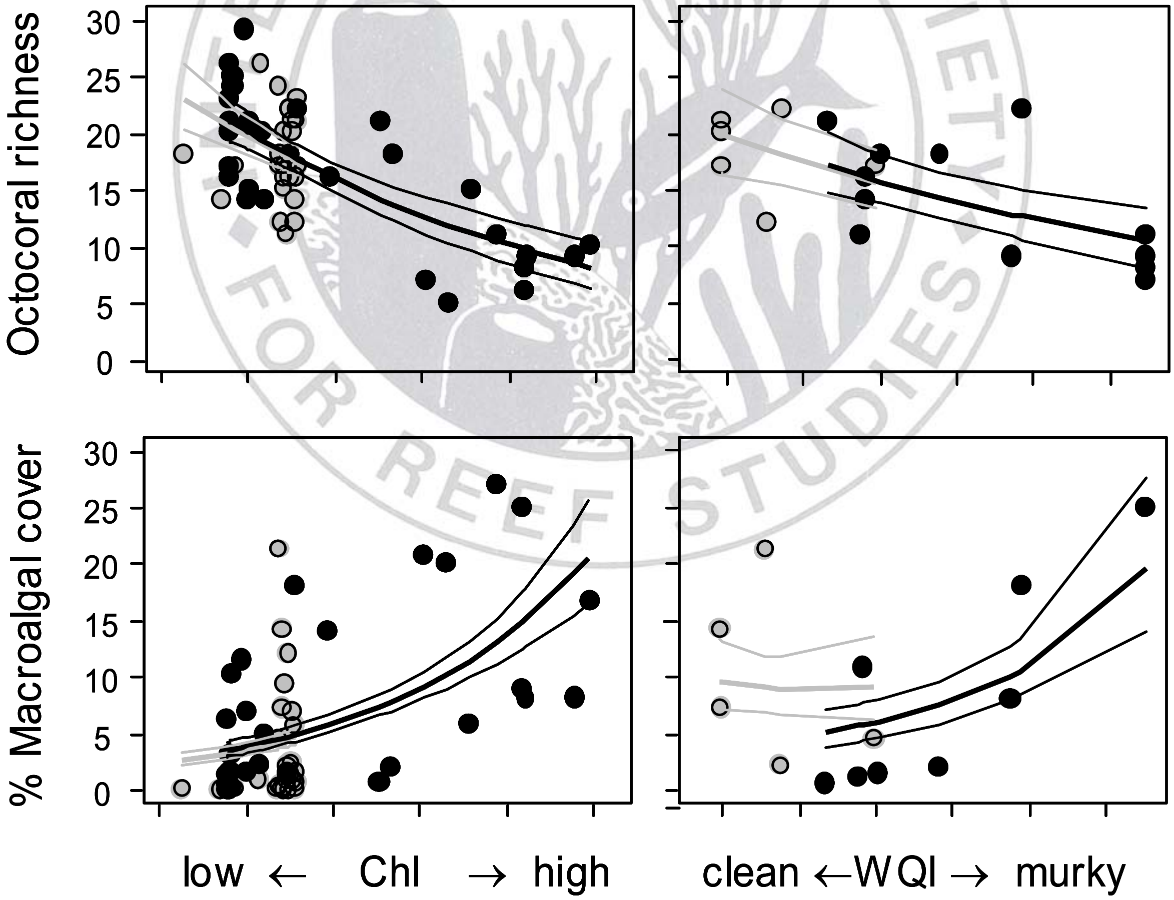


Figure 1: *Changes in the taxonomic richness of octocorals and in macroalgal cover along water quality gradients in the Great Barrier Reef; black points represent reefs exposed to runoff from agriculturally used watersheds, gray points are reefs exposed to runoff from watersheds with little agriculture.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

Shifts from coral to macroalgal dominance

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

Internal bioerosion

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

Increased susceptibility to diseases in corals

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

Changes in the abundance of coral predators

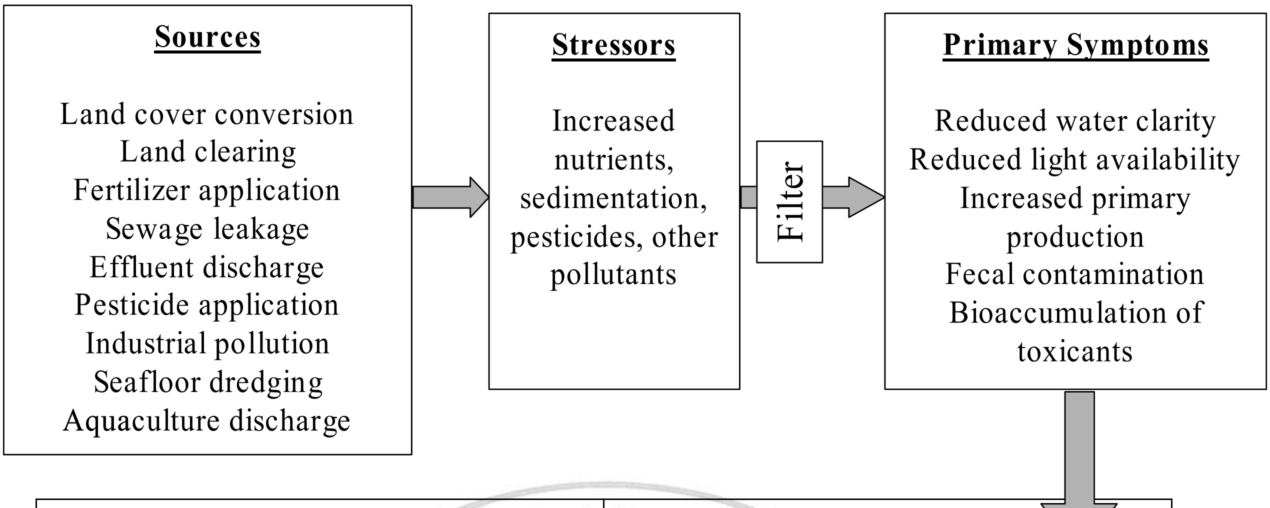
The potential increase in the frequency of population outbreaks of the crown-of-thorns seastar *Acanthaster planci* through terrestrial runoff (Birkeland 1982, Brodie 1992) represents another indirect effect, and particularly severe effect of water quality on the status of the wider coral reef ecosystem.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

Examples of coral reefs exposed to terrestrial runoff

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

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

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



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

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

WHAT NEEDS TO BE DONE?

Coastal and inshore reefs are of high economic and ecological value. They supply food and wave protection for coastal settlements, they are popular destinations for the growing dive tourism industry, and they are unique habitats for a vast number of coral reef associated plants and animals that are not found on offshore reefs. Despite a growing understanding of the effects of terrestrial runoff on coral reefs, there are often uncertainties in the interpretation of field studies of terrestrial runoff, as a result of paucity of proper river monitoring programs in the Tropics, the under-sampling of extreme runoff events, and the co-occurrence of runoff with other forms of human reef usage. Notwithstanding these uncertainties, governments of many nations have begun to recognize the seriousness of the problem of enhanced discharge of sediments, nutrients and other pollutants into the coastal waters, and accept the existing evidence that sedimentation and excess nutrients harm coral reefs. For example, an extensive review of the current scientific evidence of the effects of runoff on the Great Barrier Reef and the economic implications has now lead to a plan to "halt or reverse the decline in water quality entering the reef" (The State of Queensland and Commonwealth of Australia 2003).

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

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

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

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

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

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

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