Abstract:

Traditionally geomorphologist spent little time addressing the role of biological factors in shaping the landscape and ecologists spent little time addressing how geomorphic features effect biological factors. More recently research has been conducted to investigate the interactions between the organic and inorganic worlds. A wide range of organisms including plants, invertebrates, mammals, fish, and birds effect the form and evolution of a landscape. A landscape influenced by the interactions of plants, animals, and microorganisms are coral reefs, the most diverse marine environment on earth. Bioerosive activities of coral reef organisms significantly contribute to coral erosion and exhibit a positive correlation with increased sediment and nutrient runoff. Coral reef growth is only slightly ahead of coral reef destruction. To offset the balance could cause devastating effects for coral reefs.

INTRODUCTION

Biogeography, ecology and geomorphology share a common root in natural history developed by the broad thinking natural historians of the eighteenth and nineteenth centuries—Darwin, Lyell, and Humboldt. As natural history knowledge grew, subjects became more specialized, and linkages between the disciplines became less rigorous. More recently with the availability of powerful technology, and the applied/management focus of contemporary geomorphology, new studies have investigated the functional links between organic and inorganic components at a micro-scale. Technology has made it possible for better data collections and storage, and to analyze large quantities of diverse data. Biogeomorphology focuses on two questions: 1) the effect of landforms on the distribution and development of plants, animals and microorganisms; 2) the effect of plants, animals, and microorganisms on earth surface processes and the development of landforms (Viles 1988). The presence of biota in all environments, from algae and ice worms in ice sheet cryoconite holes to boring sea urchins on exposed limestone coasts illustrate that landscapes form and change involves a biotic component (Reed 2000). This paper focuses primarily on the second question.

L.A. Naylor, H.A. Viles, and N.E.A. Carter (2002) reviewed the current state of Biogeomorphology and provided suggestions for future development. Although there are many studies on the interactions between organisms and geomorphology in different environments, there is little
understanding of how this information is useful and where it is leading. (Naylor et al. 2002) suggest five biogeomorphical areas to focus on: the role of organisms in environmental reconstruction, trace fossil analysis, extraterrestrial geomorphology, environmental engineering, and the built environment. Challenges for biogeomorphologist include expanding the spatial and temporal coverage of datasets, investigating the role of bioprocesses in landform development, tackling scale issues, investigating the relevance of nonlinear dynamic ideas to biogeomorphology and developing better sampling and monitoring techniques. Reed (2000) notes that one of the difficulties of developing the biogeomorphic approach to any landscape category is the diversity of the plant and animal life to consider. At each site a significant understanding of the interactions can be developed but to apply this to another setting requires a more synthetic consideration to landscapes across environmental gradients.

Many biogeomorphic studies examine the processes that link the ecological and geomorphic systems such as bioweathering, bioerosion, bioconstruction, biotransformation, biostabilization, and bioprotection. Bioerosion and bioweathering examines the biological influence on the erosion of rocks and minerals. Biotransformation refers to the influence of biota to chemical transformations. Bioprotection refers to a wide range of plant, animal and microorganism interactions that reduce erosion. Bioconstruction refers to the production of sediment deposits, accretions, or accumulations by organic means. Bioconstruction can occur in three ways: organisms produce material themselves, organisms accrete material by chemically fixing particles, and inorganic cementation of organic debris. Bioerosion, bioconstruction, and bioprotection are not mutually exclusive (Spencer and Viles 2002). They share a varied, complex, and dynamic interrelationship and are connected to a range of other geomorphic processes (Naylor et al. 2001). Biogeomorphogy is particularly suited to understanding coral reefs and rocky limestone shores. Coral reefs are significantly shaped by the bioerasive and bioconstructive activities of a multitude of organisms (Spencer and Viles 2002).
Significance of Coral Reefs

Approximately 1/3 of all tropical coastlines are composed of rocky carbonate substrates and are found in over 100 countries, primarily in less economically developed regions in the tropics. These limestone-based systems provide habitat to a diverse array of plants and animals, and provide protein, building materials, and income to people in the tropics and subtropics. It is estimated that tens of millions of people depend on the coral reefs for part of their livelihood and for protein. In terms of phyla and classes, coral reefs have the greatest diversity per hectare of any ecosystem in the ocean (Birkeland 1997). Reef systems are different from other tropical shallow marine systems in their ability to build wave resistant structures that protect back-reef environments (Spencer and Viles 2002). During typhoons the damage from wave action to coastal communities is substantially less where reefs are located (Birkeland 1997). Coral reefs control sediment transport processes by protecting coastlines from erosion, create sheltered harbours, and allow for the development of shallow basins for mangrove and seagrass communities (Wood 1999). A more complete understanding of the interrelationships between geologic and biologic processes helps to provide effective coastal resource management (Spencer and Viles 2002).

Coral Reef Formation

Calcareous shells and skeletons of protists and marine plants and animals build up on oceanic shelves, banks, atolls and nearshore environments. The sediment build-up depends on the strength of the waves and currents, and the ability of the benthic community to hold the sediment in place. Organisms that project upward from the sediment, slow wave movement and trap sediment are called bafflers. Organisms that live in or directly on the sediment, holding the sediment in place are called binders. The ultimate bafflers and reef framework constructors are the stony corals. These organisms grow out and up in branching or platy morphologies. They secrete substantial amounts of calcium carbonate and trap great quantities of sediment. Encrusting algae binds the reef framework and creates massive, wave resistant coral reefs (Hallock 1997). Other densely packed, rapid growing, sessile invertebrates, that contribute to reef development include sponges, bryozoans, brachipods, molluscs, and annelids. The size and shape of the reefs are dependent on preexisting geomorphology, hydrologic regime, growth rates of the organisms,
and crustal subsidence. The living part of the reef is a thin layer of organisms attached to a rigid underlying structure (Fagerstrom 1987).

There are four types of reefs: fringing, platform, barrier and atolls. Fringing reefs are generally narrow platforms that develop in shallow waters a short distance from shore, and do not have a substantial lagoon. Platform reefs lie in sheltered seas a fair distance off shore. They have flat tops with shallow lagoons. Barrier reefs also form a distance from shore and have substantial lagoons. Atoll reefs form a horseshoe or ring-shaped reefs around volcanic islands. These reef types can evolve along a continuum. Darwin surmised that as a volcano subsides a fringing reef evolves. A barrier reef forms from a fringing reef and an atoll forms from a barrier reef (Wood 1999).

Coral reef growth occurs through coral-zooxanthellae symbiosis. Zooxanthellae are unicellular yellow-brown (dinoflagellate) algae that live symbiotically in the gastrodermis of reef-building corals. Nutrients supplied by the zooxanthellae make it possible for the corals to grow, reproduce and build reefs. Zooxanthellae provide the corals with food in the form of photosynthetic products. In return, the coral provides protection and access to light for the zooxanthellae. Because of the need for light, corals containing zooxanthellae only live in ocean waters less than 100 meters deep. They are also intolerant of low salinity, high turbidity, and temperatures below 20 degrees Celsius (Goreau et al. 1979).

(Birkeland 1997)
The structure of a reef varies from open-structure branching corals to solid hemispheric forms. Typical growth rates are 10-15mm/year in near surface waters. Calcification is strongly light-dependent and growth rates drop rapidly with depth. Due to sea level rise, and/or non-carbonate sedimentation, some reefs are considered “give-up” reefs and are submerged too deep for growth. “Catch-up” reefs are also left behind due to sea level rise but eventually catch-up if the rate of sea level rise decreases. “Keep up” reefs maintain their crests at or near sea level and may be subsequently colonized by seagrasses or mangrove communities (Spencer and Viles 2002).

Bioerosion of Coral Reefs

Activities of reef species that cause coral and coralline algae to erode are collectively called bioerosion. Bioerosion rates of limestone substrates of subtidal and intertidal environments in tropical and temperate coasts average between .5-2 mm/year as a result of physical and chemical processes (Spencer 1988) and occurs at a range of spatial and temporal scales (Spencer and Viles 2002). Individual bioerosive processes operate at a slow rate but combined may result in substantial substrate modification. (Glynn 1997) and is one of the important factors affecting the maintenance and persistence of coral reefs (Zubia and Peyrot-Clausade 2001). Rates of bioerosion and bioerosive intensity are influenced by a number of abiotic and biotic factors, particularly eutrophication (Zubia and Peyrot-Clausade 2001). Biological corrosion and biological abrasion further describe the bioerosive processes. Biological corrosion occurs when a micro-organism or macro-borer modifies the substrate but does not leave any erosive product. Biological abrasion refers to the physical processes carried out by burrowing and boring organisms that results in particulate debris production (Spencer and Viles 2002). Carbonate budget studies have shown that net reef accumulation is barely ahead of net reef loss (Glynn 1997).

Depending on the location of the organism, the bioeroder can be classified as an epilith, chasmolith, or endolith. Epilithic species live on exposed surfaces, chasmolith live in crack and holes, and endoliths live within the skeleton. Some bioeroders may change microhabitat during development (Glynn, 1997). Microborers (algae, bacteria and microorganisms) and macroborers (polychaetes, bivalves,) and grazers (fish, sea urchins and gastropods) bore and graze on the substrate using mechanical and chemical processes. Grazing organisms rasp, bite and scrape away a thin layer of coral to obtain
nutrients from endolithic algae. Specialized feeding structures such as radulas in chitons, snails, and limpets, beaklike jaw of parrotfish and radially-arranged teeth in sea urchins provide the perfect tool for scraping. Boring organisms bore into the rock for stability and protection, not for food. Abundant boring organisms include sponges, barnacles, fungi, and endolithic algae (Donn and Boardman 1988).

**Microborers**

Coralline algae contribute greatly to the development of reefs and can represent up to 90% of the live cover. Most studies have focused on the skeletons of live and dead corals. Other studies have documented the external bioerosive activities of rasping and grazing organisms (gastropods, echinoderms, and fish) on encrusting coralline algae. Less attention has been devoted to the internal bioerosive activities of encrusting red algae (Corallinaceae), the second most important biological and geological component in tropical coral reef ecosystems. To complement the current body of research, Tribollett and Payri (2001) studied the endolithic bioerosive communities and quantified the boring activity on live and dead coralline algae on an outer reef of Moorea, French Polynesia.

Tribollett and Payri (2001) randomly collected crusts on dead corals in water about 1 m in depth in March of 1998. To understand the role of the boring micro-organisms on *Hydrolithon onkodes*, the specific composition of the endolithic communities were identified. The rates of bioerosion were estimated using endolithic depth of penetration, the dimensions of the crusts, and the bored surface areas. The endolithic microflora present on the crusts consisted of several species, most notably cyanobacteria (blue-green algae). The species composition of microborers and boring patterns differed in live and dead crusts. In the dead crust a host of endolithic species were present; in the live crusts the cyanobacterium *Plectonema terebrans* were dominant. These results resemble the endolithic communities found in live and dead corals and molluscs shells.

The boring patterns differed in live and dead crusts. In live crust the endolithic microborer successfully bore at the base of the substrate. In dead crusts the microborer was more successful at the surface and its density decreases rapidly downward. The high incidence of cyanobacteria on the surface of dead crusts can be explained by the light requirements of the micro-algae. It is likely that the
microborers did not penetrate the live crusts from the surface because live cells prevent biofouling and colonization.

The results of this study conclude that the estimated amount of carbonate removed from dead crusts is four times that of live crusts of similar age thickness. Micro-endoliths are also responsible for more than 50% of the total bioerosion during the first year of bioerosion. Endoliths are direct agents of bioerosion by dissolving the carbonate substrata creating less resistance to physical events such as cyclones and storms. Endoliths also act as indirect agents of bioerosion by providing a food source for grazers, particularly after the coralline algae dies (Tribollet and Payri 2001).

**Macro-eroders**

The majority of epilithic bioeroders are herbivorous grazers that scrape the limestone rock as they feed on the algae. The eroding capabilities of the epilithic macro-eroder ranges from nondenuding and denuding herbivores to excavating species that remove large amounts of algae and limestone substrata. Sea urchins (Echinoidea) are the only animal in their phylum capable of significant bioerosion. Their highly developed "jaw", a protrusible organ consisting of five calcified teeth, are harder than the surface they scrape. Sea urchins spines' also contribute to bioerosion when employed to excavate burrows. They graze on algae growing on dead and live coral. When in low to moderate densities, sea urchins cause substantial erosion; at high densities their bioerosive activities can lead to rapid reef framework loss (Glynn 1997).

M. Carreiro-Silva and T.R. McClanahan (2001) studied the bioerosive rate of the most abundant echinoid species in three Kenyan reefs managed with various levels of environmental protection. *Echinothris diadema*, *Diadema setosum*, *Diadema savignyi*, and *Echinometra methaei* bioerosive rates were compared in: a protected reef in the Marine National Parks that had excluded fishing and coral and shell collection for the past twenty-five years; a reef protected for the past eight years in the Marine Park (referred to as newly protected); and an unprotected reefs subject to fishing and coral collection.

individuals of *D. setosum*, *S. savignyi*, and *E. diadema* were collected from Mombasa—an experimental field site representative of the shallow reef lagoons of the Kenyan coast. The gut contents of these species were analyzed for inorganic and organic particles. The inorganic particles were further broken down into eroded and reworked sediment. The reworked sediment is the previously eroded sediment transported in the current and settling on algae. To determine the amount of reworked sediment, Carreiro-Silva and McClanahan (2001) analyzed the amount of CaCO$_3$ in *Tripneustes gratilla*. *T. gratilla* is not able to abrade and erode the carbonate reef substrate. Therefore any CaCO$_3$ in the gut of this species is reworked sediment and was used to quantify the correction factor. To determine gut evacuation rates approximately 40 individuals of species *D. serosum*, *S. savignyi*, and *E. diadema* were collected at the field experimental site. Urchins' gut weight were measured over 72-hours. During this period of time urchins were not fed. This method assumes that changes in gut content over time estimates gut evacuation and therefore, erosion and organic carbon turnover. This method also assumes a steady state gut fullness.

Sea urchin population density/biomass and coral cover measurements were collected using transects each year from 1995-1997 at each study site. Sea urchin average body length measurements were converted to wet weight by length-weight regression and multiplied by the population density of each species. Individual rates of bioerosion and herbivory were multiplied by the species population densities to estimate echinoid bioerosion and herbivory rates per square meter at the three different locations along the Kenyan coast.

Large differences in sea urchin densities were found between the three reefs. Protected areas had low population densities. Unprotected reefs had two order-of-magnitude higher density and one order-of-magnitude higher sea urchin biomass. The newly protected reef had moderate density but high biomass due to the large size of *E. diadema*. The gut content analysis revealed that for all species the content in inorganic material outweighed the organic matter. Sea urchins contained 2.5-3.0 times more reworked sediment than newly eroded sediment. Sea urchin bioerosion was greater than herbivory for all studied species and proportional to body size. The highest sea urchin densities were found at the unprotected reefs and therefore the unprotected areas had the highest rate of bioerosion and herbivory. Protected reefs had twenty times lower sea urchin bioerosion and herbivory rates due to low sea urchin population densities. The newly protected reef had an intermediate number of sea urchins that caused an intermediate amount of bioerosion.
The findings of this research suggest that echinoids are important in the carbon cycle and reef development and that overfishing decreases the echinoids predators in unprotected reefs which can increase the rate of bioerosion and herbivory of echinoids. The graph below illustrates the various levels of bioerosion and herbivory of four sea urchin species in three reefs under different management policies with the greatest amount of grazing occurring in the unprotected reefs.

In some cases the bioerosive qualities of the echinoids are beneficial to the health of a coral reef. Echinoid *Diadema antillarum* helps to maintain the balance of algal growth. Intermediate densities of *Diadema* sp. provides a moderate amount of grazing to suppress algal growth and allow coral planular larvae settlement and survival. The decrease in *Diadema* sp. has contributed to the demise of some Caribbean reefs (Sammarco 1996).
One macroborer that causes devastating effects on coral reefs is the crown-of-thorns starfish *Acanthaster planci*. Normal densities of *Acanthaster planci* on coral reefs is between 6 and 20 km². An outbreak of the sea star may result in densities up to 500 km². Percentage of coral cover can decline from 78% to 2% in 6 months. The Great Barrier Reef outbreaks have the best data and reveal cycles of sea star invasion. There is no overall consensus on the cause of the outbreaks but many scientists agree that nutrients from agricultural runoff contribute greatly. Others note that reduction of predation causes a population boom. It is likely that many factors contribute to create a situation ripe for *Acanthaster planci* invasion (Birkeland 1997).

**Environmental Conditions Effecting Bioerosion**

Coral reefs are degrading rapidly on a global scale due to over-fishing and dynamite fishing, habitat destruction, deforestation, nutrient enrichment and sedimentation, coral bleaching, and population explosions of *Acanthaster planci* (Sammarco 1996). Environmental conditions such as the availability of shelter, water and nutrients may encourage an organism to bore into a substrate. Peyrot-Clausade et al. (1995) found an increase in cyanobacterial microboring species *Mastigocoleus testarum* and *Plectonema terebrans* and grazing of *Echinometra matthei* with elevated sewage levels at five sites in French Polynesia. Sediments and nutrients are usually considered the greatest threat to coral reefs (Birkeland 1997). For instance, over four times the amount of sediment, nitrogen, phosphorus enter the marine environment off the Queensland coast than before western agriculture began (Birkeland 1997). Increased water temperatures and decreased water levels encourage bioeroding species (Spencer and Viles 2002).

Bioerosion rates can also be effected by coral bleaching. Due to global warming, coral bleaching is increasing around the world. Scleractinian corals are particularly susceptible since they can live only within a narrow range of temperatures (22°C-28°C). If exposed to temperatures outside of this range, many coral species lose their zooxanthellae and tissue pigment (coral bleaching). The widespread scleractinian coral mortality is exacerbated by external bioerosion. One of the most severe cases was reported off Panama and the Galapagos Islands. An expansive coral community (*Pocillopora damicornia*) died after an intense El Nino Southern Oscillation event: 70-90% mortality off of Panama and 95% mortality off of the Galapagos. The increase in dead coral increased echinoid populations to the
point that net bioerosion in Panama 10-20 kg/m²/year and in the Galapagos 20-40 kg/m²/year are larger than the net carbonate production (Sammarco 1996).

To help determine coral reef health, coral growth rates based on the vertical extension measurements are frequently used. The assumption is that corals exposed to environmental stresses such as nutrient loading have lower vertical extension rates than corals not exposed to environmental stresses. Yet some studies indicated that coral vertical extension rates are the same and sometimes greater near sewage outfalls or near areas with moderate nutrient loading associated with agricultural runoff or aquaculture. Edinger et al. (2000) examined thirteen coral reefs in Indonesia to determine if massive coral growth rates or vertical extension rates of *Porites lobata* are good indicators of overall coral reef health. Six of the coral reefs are influenced by land-based pollution and seven of the reefs are not associated with land-based pollution. Edinger et al. (2000) also investigated the relationship between live coral cover, algae cover, non-calcified invertebrates, and bioerosion in the same regions. They also compared coral skeletal density and coral calcification in five Java Sea reefs exposed to various levels of nutrients and sediments.

Thirteen reefs were sampled from three regions of Indonesia: Java Sea, Ambon, and south Sulawesi. Environmental variables measured included: water clarity, maximum depth of coral growth, sea surface temperature, salinity, chlorophyll A concentration, nitrate and phosphate concentration, suspended particulate matter concentration, total downward sediment flux into sediment traps, and light intensity. Transects were used to measure percent coverage of live and dead corals, algae, fauna and abiotic substrates. X-rays were used to determine bioerosion intensity and coral growth rate. Bioerosion intensity was determined as the percent of cross-sectional area removed by boring organisms. Calcification rates were calculated as density of the coral (g/cm³) *linear extension rate (mm/yr). Gross carbonate production minus bioerosion equals net carbonate production. The relationship between vertical reef health parameters (extension rates, coral density, and bioerosion density) and environmental stresses were assessed using correlation and linear regression analysis (ibid 2000).
The results of this study are best described by the illustration above. Essentially Indonesian corals located in relatively unpolluted areas of and in areas subject to high eutrophication and sedimentation have similar vertical extension growth rates before they reach a threshold level. Percent coral cover decreases and bioerosion intensity increases substantially as the waters become more polluted. This graph demonstrates that coral growth rates are not a good indicator of coral reef health. To determine net reef growth vs. net reef erosion it is also necessary to measure other parameters of coral reef health such as percent live coral cover and bioerosion intensity (Edinger et al. 2000).

This article provides an interdisciplinary approach to understanding the health of a coral reef. Six researchers from five different disciplines were involved to collect and synthesize the information presented. To understand these interactions one must consider the interrelations between biological and geomorphic processes. Since coral reefs and bioeroders are living organisms, pollution has a significant influence on the morphology of the corals, and on the net coral growth and net coral erosion. In this study bioerosion intensity increases in polluted areas with high eutrophic levels and sedimentation. Many of the bioeroding organisms feed on bacteria and marine detritus, associated with eutrophic conditions.

Zubia and Peyrot-Clausade (2001) also investigate the affect of various levels of eutrophication on the bioerosion patterns of grazing and boring organisms on the reef flat of La Saline in Reunion, Indian
Ocean. The aim of their study was to estimate the intensity of internal bioerosion of microflora and fauna of dead *Acropora formosa*--a branching scleractinian. Zubia and Peyrot-Clausade (2001) found that the main bioerosive agents of dead *Acropora formosa* were boring endolithic microflora (*Plectonema terebrans, Mastigocoleus, and Ostreobium quekettii*) whose boring activities were four times greater than the boring fauna. Microborers were absent on dead *Acropora*. Under high eutrophic levels *Acropora* had more surface area bored by microflora (30.81% of CaCO₃ eroded) than in undisturbed sites. The biomass of the boring flora was also higher under eutrophic conditions. The rates of microflora bioerosion were also higher in grazed substrates than in ungrazed substrates. Potentially the constant removal of substrate by grazers facilitates deeper penetration in grazed *Acropora*.

The most common method of assessing bioerosion intensity on modern coral reefs is to measure the area removed from cross-sections of corals, using X-rays, or photographs as described with Edinger et al. (2000). These methods are time consuming, require computer image analysis--often unavailable in the developing world, and require killing live coral. Holmes *et al.* (2000) investigated a less expensive method of determining coral reef health and bioerosive intensity on coral rubble. This technique, called non-destructive rapid reef assessment (RRA), does not require expensive and technical skill to make and analyze X-rays. It also does not require destruction of live coral heads.

Off the coast of Indonesia Holmes *et al.* (2000) collected coral rubble samples ten pieces of rubble at 3 m depth, along 10, 1 m long wide and 5 m wide transects. Five random cuts were made across the long axis of each piece of rubble. Each piece was scored (0-5) for presence of absence of bioeroding organisms. The length of each rubble, and the maximum and minimum diameters of the center segment were used to calculate the approximate volume of each piece. Bioerosion intensity was determined as the average bioerosion score of the ten pieces of rubble collected per sample. Both techniques showed that bioerosion levels are positively correlated with eutrophication variables. The advantage of the rapid reef assessment is that it is inexpensive, requires little infrastructure or training for students, volunteers, and divers, and is suitable for community-based reef monitoring efforts.
SUMMARY AND CONCLUSIONS

Coral reefs are very important topographic oceanic features. They help prevent coastal erosion, create mangroves and sheltered harbors, and provide income and sustenance to millions of people. Per hectare, coral reefs are considered the most ecologically diverse marine ecosystem. Since these topographic features consist of organic and inorganic matter, investigations of coral reef morphology must use an interdisciplinary, biogeomorphological approach.

The very thin live layer of coral reefs, made up of coral colonies, bryozoans, coralline algae, mussels, sponges, and a host of other organisms, is highly vulnerable to environmental change such as: an increase in nutrients, sediments, or changes in predator prey relationships. Since coral reefs can only survive in a limited temperature range, an increase in water temperatures due to global warming is particularly damaging. Bioerosion, the erosive activities of reef species, is one of the more important factors affecting the health of coral reefs. Bioerosive rates of sea urchins and other organisms has been shown to significantly increase with higher level of nutrients and decrease level of predation. Bioerosion intensity/rates is also found to be higher in dead coral and coralline algae than live coral and coralline algae. Measuring vertical growth rates is one way of calculating the health of a coral. For a more complete assessment of coral health, bioerosion intensity and percent cover of algae vs. live coral is important to measure. Less invasive techniques include the Rapid Reef Assessment that can be implemented with volunteer support.

To preserve coral reef environments, better control of terrestrial runoff of nutrients and sediment, and more protection from coral destructive activities such as overfishing and dynamite fishing, curio collections, water pollution, and damage by boats needs to be addressed through policy and education. Coral reef growth is only slightly ahead of coral reef destruction. To offset the balance could cause devastating for the coral reef oceanscape.
Cited References


