APPENDIX II

REVIEW OF THE EFFECTS OF SILTATION ON CORALS AND CORAL COMMUNITIES

BY

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Effects of Siltation on Corals and Coral Communities

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Introduction

Any analysis of the effects of siltation on coral reefs necessarily revolves around the siltation tolerances of corals. Corals are the basic constructional organisms of the reef, and are central to the integrity of the reef community. Changes in coral reef communities depend on the responses to siltation of the individual component species. Johannes (1975) has pointed out that selective mortality of corals results in the migration or death of other fauna. In other words, the environmental tolerances of the reef community cannot exceed those of the component corals. This is not to say that other organisms may not have narrower tolerances or are not integral parts of the community. However the corals are so important ecologically and visually that their needs at least must be met.

Coral reef ecosystems are very sensitive to ecological change for three reasons (Pastorok and Bilyard, 1985):

- corals have narrow physiological tolerances,
- key species interactions are susceptible to pollutant stresses, and
- effects of toxic materials may be greater at highwater temperatures.

This review concentrates on the effects of particulate materials, rather than nutrient or toxic pollution. Firstly the effects on individual species are summarised, secondly the consequent changes in coral communities are noted, and finally a qualitative summary of the effects of siltation is given with observations on the research which needs to be done.

Deleterious Effects of Siltation on Reefs

Although healthy coral communities have been observed growing in generally turbid waters (e.g. Marshall and Orr,1931; Roy and Smith,1971), it is also clear that many reefs have been extensively damaged or destroyed by excessive siltation. Johannes (1975) summarised several studies, particularly those which ocurred in response to man's activities, such as increased sediment yields due to poor land management, dredging spoil, mill waste and sewage pollution. Pastorok and Bilyard (1985) have reviewed the effects of sewage pollution, including the detrimental effects of increased levels of nutrients, sediments and toxic substances.

Dodge and Vaisnys (1977) compared both living and dead corals from two areas in Bermuda : 1) undisturbed reefs and 2) reefs in a harbour where dredging had occurred 35 years previously. The dredged area showed a lower density of living specimens, a lower proportion of live/dead corals, and altered relative species abundances. Two species of brain coral, *Diploria strigosa* and *D.labyrinthiformis* are equally represented on undisturbed reefs and in dead coral populations from the dredged harbour. However *D. labyrinthiformis*, a species demonstrably more capable of sediment rejection, is the dominant living form inside the harbour. Analysis of the growth patterns of the dead harbour corals showed an abrupt decrease in growth rate, lasting up to nine years before death. In summary,

the dredging and subsequent sedimentation in the harbour produced mass coral mortality, although the effects varied from species to species, and it appears the effects of the dredging lasted several years after the event. Unfortunately there are no data on the amount of turbidity induced at the time, nor the pattern over time of its dispersal.

The immediate effects of suspended sediment were recorded by Bak (1978) during the dredging of a bay channel in Curacao. For two days the suspended sediment cloud reduced light levels at 12-13m water depth from the normal 30% to less than 1% of surface illumination. For two more days light levels were less than 6% surface levels. The dredge continued working for a further 14 days during which light levels were less drastically depressed due to currents sweeping the sediment in other directions. On the fifth day of dredging, the reef was covered by 10mm of sediment, apart from the corals which had removed the sediment from their colonies. One coral, platey *Porites astreoides*, appeared unable to dislodge the sediment, became covered and wholly or partly died. All measured corals showed an abrupt decrease in coral calcification rates (up to 33%), and rates remained depressed for more than one month.

A fringing reef near Cahuita, Costa Rica is under siltation stress due to increased sediment influx following regional deforestation of the catchment (Cortes and Risk, 1985). Suspended particulate matter analyses for waters over the reef were in the range 0.2-54.0 ppm. Sediment resuspension rates were much higher than reported for other Caribbean reefs. The study showed that the depths at which corals occurred were shallower in these turbid waters than for the same species in clear waters in the Caribbean, and that coral growth rates were inversely proportional to sediment resuspension rates.

Not all major sediment influxes have disastrous effects. For instance, Dollar and Grigg (1981) reported minimal damage to a reef 14 days after a major spill of kaolin from a grounded freighter. The minimal effects could be due to the fine grained and inert nature of the kaolin, but is probably mainly due to the off-reef transport of the material (see their Figure 5).

In situations where suspended sediment is due to terrestrial influx, the deleterious effect of the sediment is compounded and in some cases outweighed by the osmotic problems resulting from immersion of the corals in low salinity waters (e.g. Rainford, 1925; Goreau, 1964; Banner, 1968). Following Hurricane Flora in 1964, Goreau (1964) reported immense influxes of sediment and fresh water to the sea off Jamaica. Two days of heavy rain resulted in offshore river plumes which lowered near-shore salinities to 3 ppt for two days and to 30 ppt for five weeks. Massive bleaching and expulsion of zooxanthellae from the reef corals occurred. That these effects were due primarily to the fresh water is indicated by three facts : 1) the bleaching and expulsion was confined to a horizontal zone about 3m deep cutting across the topography, 2) the depth of bleaching was greater closer to the source of freshwater influx, and 3) the restriction of bleaching to the surface layers whereas sediment shading should affect deeper zones more than shallow ones.

Laboratory studies to quantify the effects of suspended sediment on corals have been conducted by Bak and Elgershuizen (1976), and Dodge (1982). Bak and Elgerhuizen (1976) compared the rejection behaviours of 19 Caribbean hermatypic corals to sand, oil-sand mixtures and carborundum powder. Rejection of oil-sand particles and of clean sand show similar patterns, with some species showing greater efficiency for carborundum compared to sand, and some species the reverse. Rejection times are generally less than 10 hours and commonly less than 4 hours. The rejection times were longer for larger sand placements on the coral, being typically less than four hours for 0.75g sand but 5-15 hours for 3.0g of sand.

In contrast to the direct addition of sediment to the corals by Bak and Elgerhuizen (1976), a study by Dodge (1982) evaluated the effects on a coral of chronic (6 weeks) exposure to suspended (100 ppm) commercial drilling mud. The coral studied was the common and ecologically important Caribbean species *Montastrea annularis*. Upward, linear growth rate was significantly depressed and

there was increased mortality. Szmant-Froelich et al. (1981) working on the same corals, found calcification rates were only 47% after four weeks and 16% after six weeks. Corals exposed to 1 and 10 ppm suspended sediment levels showed none of these adverse effects.

These studies have established the deleterious effect of substantial siltation on corals. It is clear that species vary in their tolerance of siltation, and particularly that intermittent siltation can be tolerated where chronic sedimentation cannot. However, there are very few data on how frequently siltation episodes can be tolerated, or what are the critical levels of suspended sediment before corals are adversely affected. The following points can be made :

1) Corals can thrive in ambient light levels 30% of surface illumination and grow in zones of <5% surface illumination. Data of Motoda (1939) show light levels in clear water are 5% of surface at 20m depth.

2) Suspended sediments attenuate the light levels and therefore can be expected to affect increasingly the corals growing in deeper waters. In areas of chronic turbidity this may impose a shallower than normal limit for coral growth.

3) Laboratory experiments indicate severe effects on coral in shallow water due to 100ppm suspended sediment, but no effects due to 10ppm. Field data of Motoda (1939) confirm vigorous coral growth at 10m water depth with 25ppm suspended material. Field data of Cortes and Risk (1985) indicate 5ppm suspended particulate matter can inhibit coral growth where there are high rates of sediment resuspension. The sensitivity of some common coral species to sedimentation has been summarised by Pastorok and Bilyard (1985). However most of these data are for Atlantic corals.

4) Despite the known dependence of calcification rates on light levels (Goreau, 1959), the relationship is not simple. For instance, not all coral species show a direct correlation between calcification and sun hours (Bak,1974), some coral species calcify more slowly in shallower rather than deeper water (Barnes and Taylor, 1973; Bak, 1976), and decreased calcification rates continue well after light levels have returned to normal following dredging operations, presumably due to metabolic shock (Dodge and Vaisnys, 1977; Bak, 1978).

5) The deleterious effects of a major influx of suspended sediment may outlast the immediate environmental problem by a period of months to years. This long term damage may be due to continued resuspension of introduced sediment or to poorly known effects of metabolic shock.

6) Fringing coral reefs do grow in areas of chronic sediment resuspension (e.g. Marshall and Orr (1931), where the amount of suspended sediment is controlled by local winds and perhaps tidal conditions. Continued coral growth requires constant water flushing to prevent sediment blanketing the corals. Data on the daily and weekly variations in turbidity, and the relation to coral communities have not been published.

7) The deleterious consequences of suspended sediments on corals could be due to six effects (Bak, 1978; Lasker, 1980; Cortes and Risk, 1985):

- Suspended sediment causes lower light levels which depress calcification rates.
- Sediment blankets the coral causing suffocation.
- Energy used in removing the sediment saps the vitality of the polyp.
- Suspended sediment has unfavourable effects on the plankton food sources for the corals.
- Suspended sediment and soft sediment cover on the substrate may prevent successful settlement of planulae.

In cases where the suspended sediment is due to terrestrial runoff, the associated fresh waters may cause major osmotic problems for the polyps.

Mechanisms of Sediment Rejection by Corals

Most hermatypic corals are efficient sediment rejectors compared to other benthic organisms, considering the observation of Bak (1978) that only the corals were clean following sediment influx, while the rest of the reef had a 10mm coating of sediment. Corals employ four mechanims of sediment rejection (Hubbard and Pocock, 1972) :

Distension of the body mass by water intake to cause sediment to slough off. Since there appears to be no coordinated effort across the colony, larger corals would be particularly disadvantaged. Mucus secretion and the entangling of sediment followed by removal of the mass by ciliary action. Removal of particles by tentacles. Ciliary beat producing currents to sweep particles off the polyp.

The different strategies vary between species (Hubbard and Pocock,1972), and seemingly under different conditions for the same species, since the same species performed differently in the studies of Hubbard and Pocock (1972) and of Bak and Elgerhuizen (1976).

Bak and Elgershuizen (1976) note that the inital polyp response to sediment rain is contraction followed by expansion, and the clearing of the surface by ciliary currents and movement of tentacles. Mucus trapping tends to delay clearing of detritus from the polyp surface. Even the one coral may use different strategies to cope with different sediment sizes. For instance, *Montastrea cavernosa* was observed to remove large oil-sand aggregates (30mm) by tentacular action and polyp distension, but smaller particles by ciliary action. However silt-size (to 63 micron) sediment is the coarsest material normally removed easily by corals (Hubbard and Pocock,1972).

In general it seems individual polyp behaviour is more important than other features such as colony form and calyx density for efficient sediment rejection. However, Lasker (1980) argues that both colony form and species behaviour are important, contributing to separate passive and active phases of sediment removal. Passive removal is promoted by convex colonies and tall polyps, while active removal involves action by the polyp. The success of continued sediment removal and continued coral growth will depend on the coral morphology and habitat. It has been observed that a single species has separate morphologies (displays different ecomorphs) in clear versus turbid waters (Laborel, 1969; Loya, 1972). Branched corals through which suspended mud can easily pass are clearly more adapted to turbid situations than platey forms. For instance Rogers (1979) found Rogers (1979) found *Acropora cervicornis* colonies were not affected by applied sediments even though they were killed by shading. Vigorous water movement can help remove particles so that an individual coral is not blanketed for extensive periods.

Responses of Coral Communities to Shading and Turbid Waters

Coral communities growing in turbid waters differ from those in clear waters, in three main ways : lesser coral cover, lower growth rates, lower diversity and different species composition. Dying coral and prolific algal growth are a common response especially where nutrient and sediment influx occur together (e.g. Weiss and Goddard,1977).

The deleterious effects of high sedimentation rates (Fig.A1) on coral communities has been documented in Guam by Randall and Birkeland (1978). Pastorok and Bilyard (1985) summarised the study "*Based on their data, Randall and Birkeland (1978) would expect a 'depauperate coral community of less than 10 species covering less than 2% of the substrate' where the average sediment loads are about 160 to 220 mg/sq.cm/day. A 'rich coral community of over 100 species covering over 12% of the solid substrate' is expected where average sedimentation rates are about 5 to 32 mg/sq.cm/day.*"

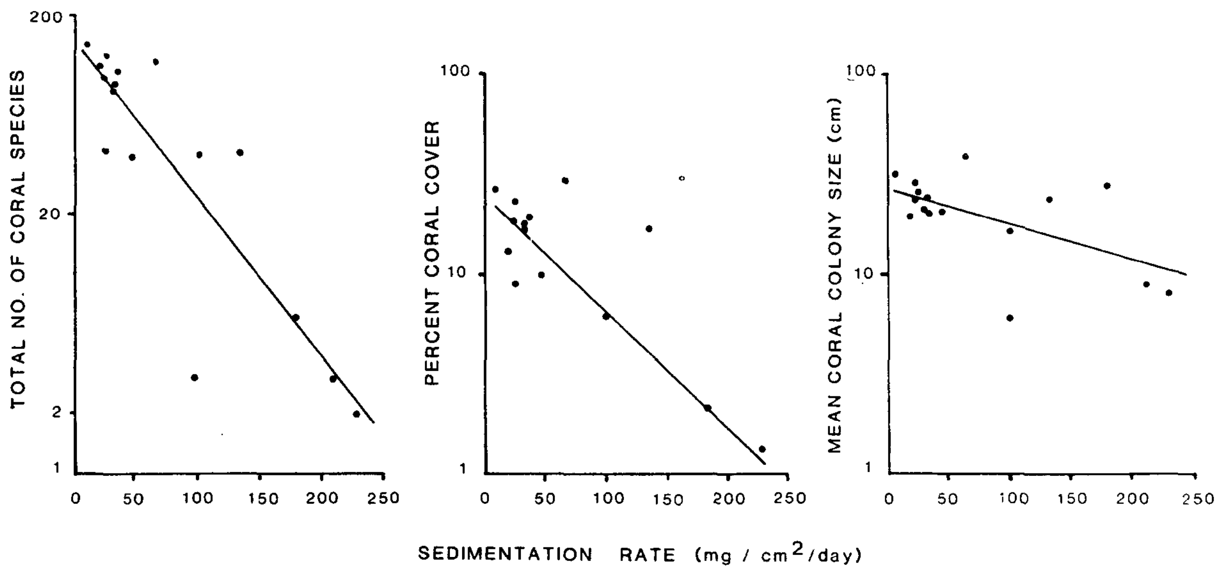

Figure A1. *Coral species richness, percent cover, and colony size as a function of sedimentation rate, Guam (from Pastorok and Bilyard, 1985, based on data from Randall and Birkeland, 1978)*

SEDIMENTATION RATE $mg/cm^2/day$	DEGREE OF IMPACT
1 - 10	Slight to moderate Decreaseed abundance Altered growth forms Decreased growth rates Possible reductions in recruitment Possible reductions in numbers of species
10 - 50	Moderate to severe Greatly decreased abundance Greatly decreased growth rates Predominance of altered growth forms Reduced recruitment Decreased numbers of species Possible invasions of opportunistic species
> 50	Severe to catastrophic Severely decreased abundance Severe degradation of communities Most species excluded Many colonies die Recruitment severely reduced Regeneration slowed or stopped Invasion by opportunistic species

Table 1. *Estimated degree of impact of various sedimentation rates on coral communities (from Pastorak & Bilyard, 1985).*

Similarly coral cover in clear waters averages 60-80% and extends to depths exceeding 15m, but averages only 30% in turbid areas where it is present only to 9m water depth (e.g. in the Fanning Lagoon; Roy and Smith,1979). Lower coral growth rates in turbid areas have also been documented by Aller and Dodge (1974) and Cortes and Risk (1985). Lower species diversity is found in areas of higher sediment resuspension (Aller and Dodge,1974) and sediment settling (Loya,1972,1976). Similarly, Bull (1982) found coral growth on a fringing reef in the Great Barrier Reef, where there was higher deposition of finer sediment, displayed lower species diversity, lower coral cover and a shallower limit to coral growth.

It is well established that reefs with high rates of sedimentation and resuspension have characteristic faunas, and that corals which dominate such reefs are subordinate or absent on clear water reefs (Lewis, 1960; Roy and Smith, 1971; Loya, 1976; Bull, 1982; Done, 1982). Some of these dominant species have been demonstrated to be efficient sediment rejectors in laboratory experiments (Bak and Elgershuizen, 1976).

A corollary to these observations is that increased sedimentation and resuspension rates should alter the community structure of a reef. Several studies confirm this expectation. For instance Dodge and Vaisnys (1977) demonstrated the change in community structure which followed siltation due to harbour dredging.

Summary

The response of a coral reef to increased siltation, either greater influx of turbid waters or greater resuspension, will vary according to the species present and the degree, type and duration of the siltation. Quantification of the threshold levels for individual species or communities is almost impossible with present data. Pastorok and Bilyard (1985) summarised the available data as a qualitative impact scale (Table 1). Most present data on coral and coral community responses to siltation have been derived from Atlantic species. In general it seems that sewage and other toxic substances have little impact in well flushed environments, such as exist in coastal and offshore situations in the Great Barrier Reef, particularly where there is so little pollution. However, increased sedimentation is a more likely problem, especially in near coastal situations, yet there are virtually no data on the effects of increased sedimentation in Indo-Pacific corals. Medium to long term studies are needed on Great Barrier Reef coral community responses to increased sedimentation.