

Coastal nutrification in Brazil: A review of the role of nutrient excess on coral reef demise

Ozeas S. Costa Jr.^{a,*}, Malcolm Nimmo^b, Martin J. Attrill^b

^a *The Ohio State University at Mansfield, School of Earth Sciences, 1680 University Drive, Mansfield, OH 44906, USA*

^b *University of Plymouth, Plymouth Environmental Research Centre, Drake Circus, Plymouth PL48AA, UK*

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Abstract

Coral reefs worldwide have suffered extensive decline in density and diversity. Brazilian coral reefs were spared natural acute stresses that have had key influences on Caribbean and Indo-Pacific corals. Their demise is due mainly to human activities, especially nutrification. This study presents a review of the current state of knowledge of coastal nutrification in Brazil and its role in coral reef demise. Using examples from Bahia State, we describe how nutrient excess has driven a shift from coral to algal dominance of benthic production. Increases in chlorophyll concentration and abundance of filter feeders are also reported. The ecological significance of seasonality and submarine groundwater discharge is discussed, and the article concludes by examining the implications of nutrification for coastal resources management.

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1. Introduction

The traditional image of coral reefs as luxuriant forests of life and colour has dramatically changed during the past 20 years. Many coral reefs worldwide have suffered extensive decline in coral diversity and density, with increasing cover of non-coralline, fleshy, and filamentous macroalgae (Done, 1992; Wilkinson, 1992; Hughes, 1994; McCook, 1999; Hughes et al., 1999). Various events have been invoked to explain this change, including tropical storms (Knowlton et al., 1981; Rogers et al., 1991; Blair et al., 1994; Ostrander et al., 2000), coral bleaching (Williams and Bunkley-Williams, 1990; Meesters and Bak, 1993; Brown et al., 1994; Glynn, 1996), sedimentation (Rogers, 1990; Cortes, 1993), coral diseases (Gladfelter, 1982; Edmunds, 1991; Antonius, 1995; Aronson et al., 1998; Goreau et al., 1998), reduced herbivory (Carpenter, 1990a,b; Hay, 1997; Hughes et al., 1987; Aronson and Precht, 2000),

and eutrophication (Hallock and Schlager, 1986; Tomascik and Sander, 1987; Hunte and Wittenberg, 1992; Naim, 1993).

Such a wide range of stresses act at different temporal and spatial scales and can be categorised as either acute (e.g., violent storms, freshwater inundation, outbreak of predators) or chronic (e.g., regular sediment, sewage and nutrients inputs, diseases, effects of tourism), as described in the works by Kinsey (1988), Connell (1997), and Connell et al. (1997). These authors note that coral reefs recover rapidly from acute stresses, but chronic stresses have an intense and prolonged impact by destabilising the community structure of the reef, which may also inhibit coral recovery after destructive events. Bythell et al. (2000) observe that Caribbean reefs destroyed by disease in the 1970s are showing little or no recovery, whereas sites less than a kilometer away devastated by Hurricane Hugo in 1989 are recovering well.

Because the Brazilian coast is not affected by hurricanes, nor has it experienced infestations of crown-of-thorns starfish (COTS) or other predators, the reefs were spared from natural acute stresses that influenced Caribbean and

* Corresponding author. Tel.: +1 419 755 3908; fax: +1 419 755 4367.
E-mail address: costa.47@osu.edu (O.S. Costa Jr.).

Indo-Pacific areas. Moreover, there are no reports of diseases in Brazilian corals, and bleaching events normally have recovery rates higher than 70% (Migotto, 1997; Castro and Pires, 1999). Therefore, though a sea-level drop of about 5 m during the last 8000 years played an important role in defining the reef structure and morphology (Leão, 1982), all major stresses on the Brazilian reefs can be related to human activities. These include sedimentation caused by upstream land practices and extensive logging of Brazil's Atlantic coastal forest (Addad and Martins-Neto, 2000; Werner et al., 2000), overfishing (Rocha, 1997), tourism-related activities (Leão, 1996), and nutrient enrichment or nutrification (Costa et al., 2000; Costa et al., 2002).

2. Nutrification and coral reefs

Although there is growing recognition that reefs are not limited to oligotrophic environments (e.g., reviews by Hatcher, 1997; Szmant, 1997), there is also an established consensus that, in healthy coral reefs, biological activity in the plankton community is trivial relative to the benthos. Margalef (1968) was among the first to point to the scarcity of hermatypic (reef-building) corals in high-nutrient environments. Since then, nutrient fluxes that support the productivity of coral reefs have been the focus of many studies of reef ecology and biogeochemistry (e.g., D'Elia, 1988; Crossland, 1983; Entsch et al., 1983; Davies, 1984; Hallock and Schlager, 1986; Atkinson, 1988; Sorokin, 1990; Bell, 1992; Delgado and Lapointe, 1994; Hoegh-Guldberg et al., 1997; Lapointe, 1997; Charpy et al., 1998; Larned, 1998; Ferrier-Pagès et al., 2000; Costa et al., 2002).

Agriculture and urban activities are major sources of phosphorus and nitrogen to aquatic ecosystems. Atmospheric deposition further contributes as a source of nitrogen. These nonpoint inputs of nutrients are difficult to measure and regulate because they derive from activities dispersed over wide areas of land and have variable timing related to the effects of weather (Carpenter et al., 1998). In coral-reef ecosystems, nutrification can introduce an imbalance in the exchange of nutrients between the zooxanthellae (symbiotic algae) and the host coral (see Appendix A) (Hoegh-Guldberg and Smith, 1989; Muscatine et al., 1989; Stambler et al., 1991; Koop et al., 2001). It can also reduce light penetration to the reef due to nutrient-stimulated phytoplankton growth (Riegl and Velimirov, 1991; Genin et al., 1995) and may enhance algal growth and the proliferation of seaweed. The latter rapidly outgrow, smother, and eventually replace slow-growing coral reef, which have adapted to cope with the low nutrient concentrations typical of tropical seas.

Coral larvae settlement is also prevented (or diminished) with an increase of plankton community density, and the probability of coral larval survival declines when other plankton, especially carnivorous species, are abundant (Birkeland, 1977; Harrison and Wallace, 1990; Hunte and Wittenberg, 1992).

3. Nutrification along the Brazilian coast

Flowing down from the equator, waters from the oceanic Brazil Current induce oligotrophic and near homogeneous conditions of the chemical constituents along the inner shelf (Koenig and De Macedo, 1999). Mesotrophic or eutrophic conditions are mainly local, depending on either land-based sources (Jennerjahn et al., 1999; Ovalle et al., 1999; Dittmar and Lara, 2001) or upwelling processes (Carbonel and Valentin, 1999; Gonzalez-Rodriguez, 1994). Estuarine and coastal areas near major urban settlements are the most eutrophic (Contador and Paranhos, 1996; Jorcín, 2000), with untreated sewage discharge being one of the main sources of nutrients to coastal areas (Kjerfve et al., 1997; Carreira and Wagener, 1998).

Land impacts on offshore reefs are mitigated by efficient flushing induced by the Brazil Current (Knoppers et al., 1999). Nearshore reefs, however, are subject to the influence of a highly siliciclastic sediment influx (Leão, 1996) and receive substantial supplies of nutrients from terrigenous sources, including runoff, river discharge, and groundwater inputs (Costa et al., 2000). At these coastal reefs, the highest levels of water-column productivity and benthic algal cover are observed. For instance, Metzler et al. (1997) reports concentrations of chlorophyll *a* varying from 0.12 to 1.41 µg/L in the inshore region of Cabo Frio, Rio de Janeiro State, compared to values below 0.3 µg/L in the oceanic region.

Costa (2002) finds a similar pattern around the reefs of Porto Seguro Bay (Fig. 1), Bahia State; the offshore reef (Recife de Fora [RF]) has one-quarter the chlorophyll *a* concentrations and one-third the suspended solids concentrations compared with those encountered in nearshore reefs (Fig. 2). Differences between the two nearshore reefs, Coroa Vermelha (CV) and Ponta Grande (PG), reflect varying degrees of urbanization, and the concentration gradients relate to the distance from a localized source of pollution (e.g., urban settlement without sewerage treatment in CV), even though both reefs have the same physical characteristics.

Nutrient concentrations also decrease with increasing distance from the shore, reflecting terrestrial and nearshore sources of nutrients, both natural (e.g., rivers, mangroves, grass-bed detritus) and anthropogenic (e.g., wastewater seepage, agricultural run-off). Metzler et al. (1997) find that in oceanic waters, NO_3^- is the main form of nitrogen available for phytoplankton (64–86% of total nitrogen), whereas at the inshore station, NO_3^- represents less than 32% of the total nitrogen supply. Nonetheless, primary production is dominated by a regenerated production that relies on the recycling of nutrients within the photic zone, and the benthos are the major source of nutrients to recycling. Uptake of reduced forms of nitrogen represents, on average, 74% of total nitrogen utilized by phytoplankton in the oceanic region and 96% at the inshore station (Metzler et al., 1997).

Such an inshore-offshore gradient in nutrient concentration is also observed in southern Bahia, with total oxidized nitrogen ($\text{TON} = \text{NO}_3^- + \text{NO}_2^-$) concentrations in the

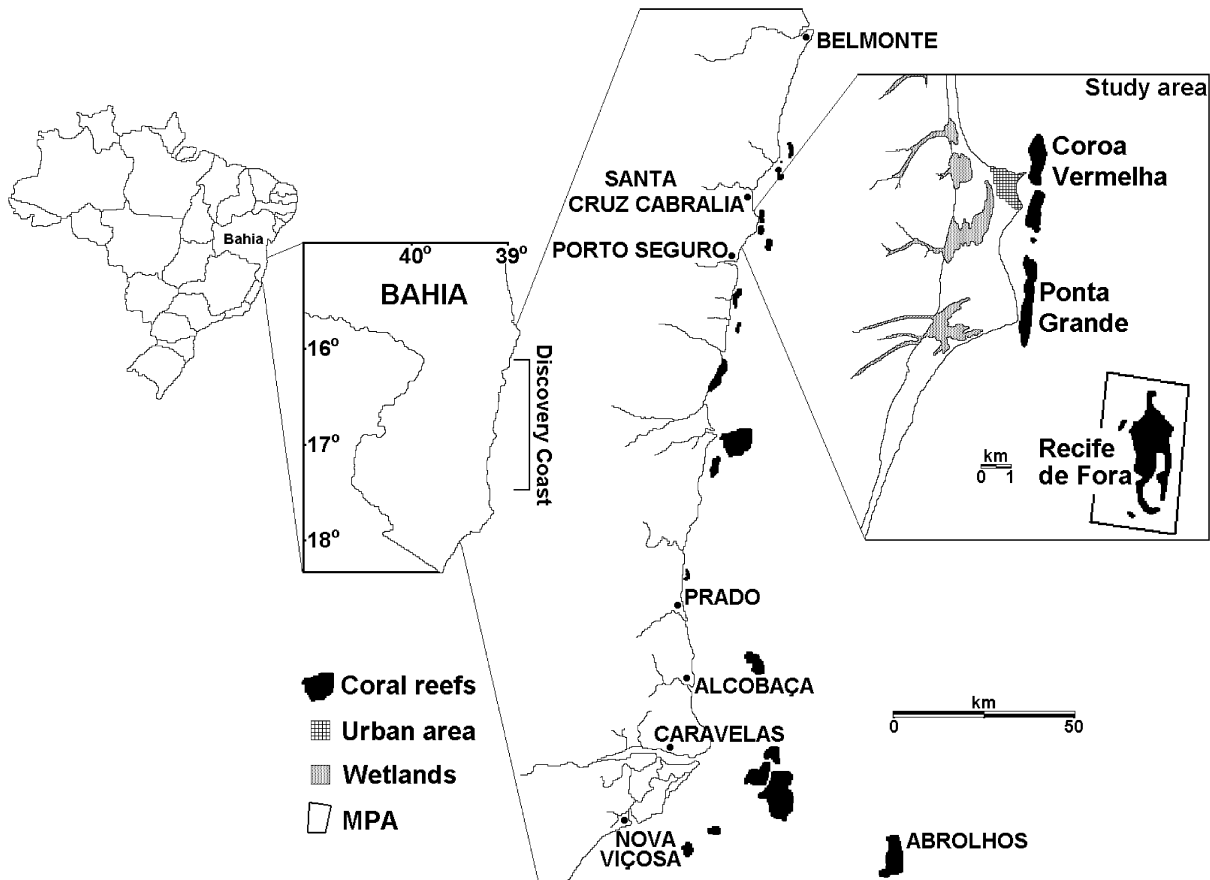


Fig. 1. Map of the Brazilian Discovery Coast, southern Bahia, Brazil, and location of the reefs studied.

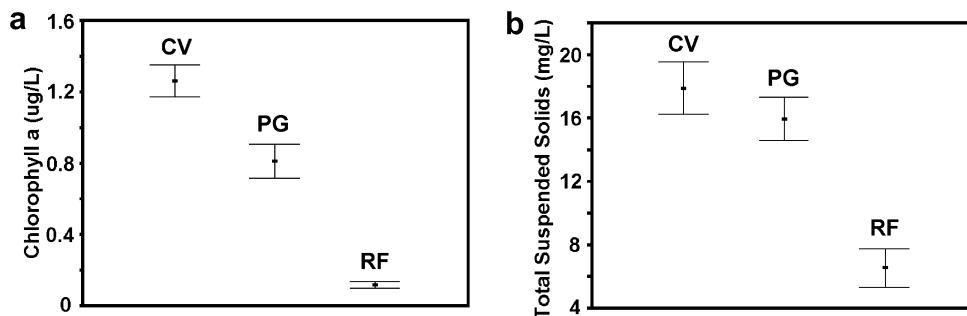


Fig. 2. Spatial variation of chlorophyll *a* and TSS concentrations measured in the water column in the study sites from southern Bahia, Brazil. CV, Coroa Vermelha; PG, Ponta Grande; RF, Recife de Fora. Bars represent means and 95% confidence intervals.

nearshore reefs varying from 1.74 to 2.81 μM during the dry season and from 1.95 to 3.64 μM during the rainy season. In contrast, the offshore reef presented TON concentrations varying from 0.41 to 0.89 μM during the dry season and 0.52–1.16 μM during the rainy season (Costa, 2002). Similar patterns are observed in soluble reactive phosphorus (SRP) and reactive silica (DSi) concentrations (Fig. 3) and correlate negatively with coral cover ($p < 0.05$), as shown in Table 1. Such a correlation suggests an adverse effect of nutrients, especially because this gradient correlates positively with the percentage cover of both algae and zoanthids ($p < 0.05$).

Coroa Vermelha also shows the most elevated nutrient concentrations of all study sites (Fig. 3), probably due to untreated sewage and wastewater contributions from the nearby urban area. Lower levels of nutrients in Ponta Grande reflect, in general, the lack of a continuous, permanent source, in addition to biological and chemical removal processes.

4. Effects of nutrification on Brazilian coral reefs

Considerable discussion and some controversy exist among scientists and conservationists with respect to the

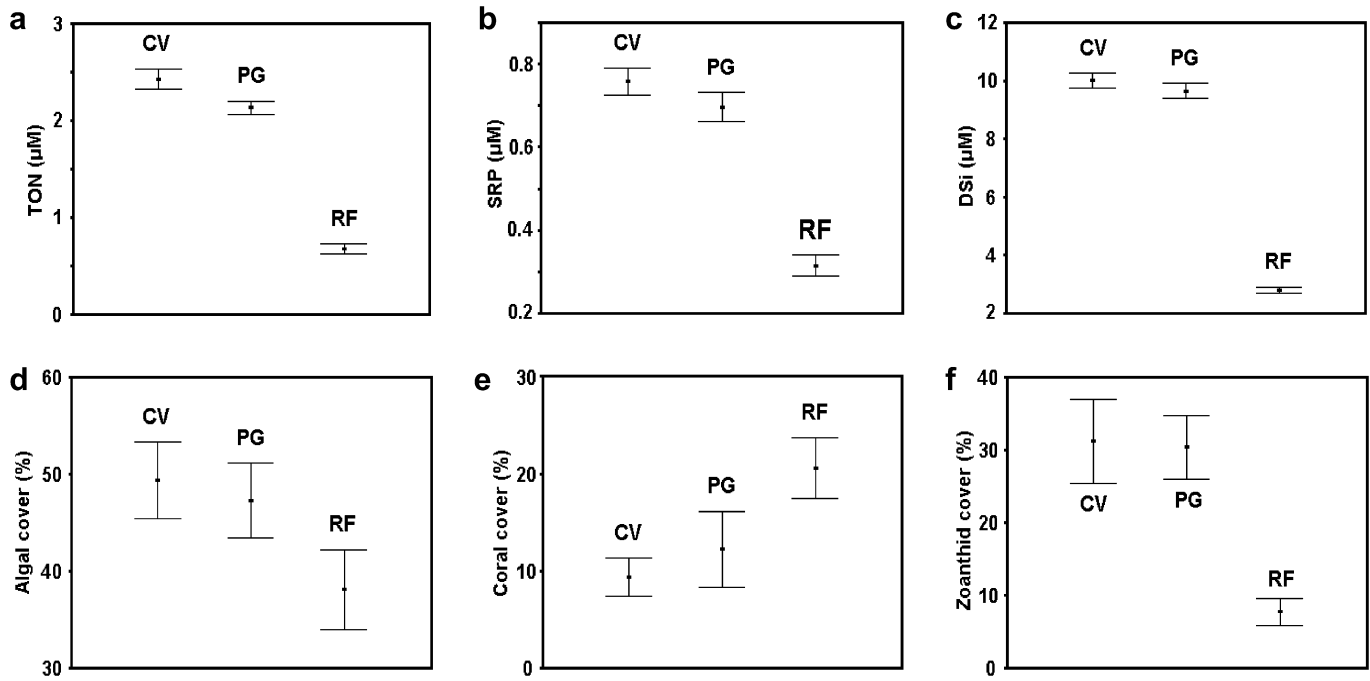


Fig. 3. Spatial variation of nutrient concentration measured in the water column (a–c) and the major groups of benthic organisms (d–f) in the study sites from southern Bahia, Brazil. Algal cover includes fleshy, turf, and coralline algae. Coral cover includes stony corals and hydrocorals. Bars represent means and 95% confidence intervals. TON, total oxidised nitrogen; SRP, soluble reactive phosphorus; DSi, reactive silica.

Table 1
Pearson's product–moment correlation between measured parameters in the study sites from southern Bahia, Brazil

	Chl <i>a</i>	TON	SRP	DSi	Algae	Coral
TON	0.801					
SRP	0.735	0.971				
DSi	0.806	0.980	0.950			
Algae	0.280	0.458	0.521	0.389		
Coral	−0.313	−0.450	−0.477	−0.389	−0.594	
Zoanthid	0.586	0.555	0.562	0.607	0.174	0.176

TON, total oxidised nitrogen; SRP, soluble reactive phosphorus; DSi, reactive silica.

role of nutrient enrichment in the degradation of coral reef communities. Until recently, the rationale that any increase in nutrient flux or concentration would provoke a community shift from coral to algal dominance was widely accepted. This assumption was based on studies that observed stimulation of primary production with increased nutrient concentrations (Kinsey and Domm, 1974; Weiss and Goddard, 1977; Smith et al., 1981; Hatcher and Larkum, 1983; Lapointe, 1985, 1997; Tomascik and Sander, 1985, 1987; Cuet et al., 1988; Kinsey, 1988; Lapointe and O'Connell, 1989; Littler et al., 1991, 1993; Bell, 1992; Lapointe et al., 1993, 1994; Naim, 1993; Delgado and Lapointe, 1994; Adey, 1998; Larned, 1998).

This assumption, however, has been challenged by more recent studies (Grigg, 1994, 1995; Larkum and Koop, 1997; Miller et al., 1999; Koop et al., 2001), which demonstrate that algal communities in some reef areas may be nutrient replete and that additions of inorganic nutrients will not

necessarily increase algal accumulation. Even if ambient nutrient concentrations are low, the flux within a given system may be great enough to deliver adequate nutrient levels to release the apparent nutrient limitation from the dominant algae. It is important to note that these studies do not challenge the idea that increasing nutrification would increase algal growth and primary productivity but rather assert it will happen only when growth is limited by the supply of that nutrient or when growth rates are not already maximal.

Although the problem of coastal eutrophication is more common in developed countries of the northern hemisphere (Paerl, 1997; Smith et al., 1999), the potential for nutrient contamination in Brazilian coastal waters is extremely high, especially near urban areas, because municipal sewage collection and treatment systems are frequently inadequate or even nonexistent. Some Brazilian nearshore reefs already receive substantial supplies of nutrients from land-based sources, such as surface runoff, submarine groundwater discharge, and untreated sewage. Widespread use of cesspits and septic tanks in urban settlements along the coast increases the nutrient concentrations of groundwater by infiltration through highly porous sandstone and beach rocks (Costa et al., 2000). As a measure of the problem, of the 812 districts in the Bahia State (the most extensive coastline in the country, 830 km long), only 282 have a sewage collection system, and only 51 (6.3% of all districts) undertake any kind of treatment before flushing into rivers, estuaries, and coastal areas (IBGE, 2002).

There are several ways nutrification may adversely affect corals and coral reef ecosystems. At the ecosystem level,

nutrient enrichment may enhance algal growth, and the proliferation of macroalgae leads to competition for space with the corals. Data derived from a southern Bahia study indicate that coral-cover increase presents a strong positive correlation with the availability of space for settlement ($r^2 = 0.572$, $p = 0.012$) and that coral cover and available space (bare areas) are higher away from the pollution source (Costa et al., 2002).

Other fast-growing organisms can gain a competitive edge over corals when the nutrient supply increases, as is the case for zoanthids, especially the genus *Palythoa*, the organisms most adapted to take advantage of an increase in nutrient concentrations in coastal areas (Costa et al., 2002). On nearshore reefs, a negative correlation exists between zoanthid and algal abundance, whereas a positive correlation occurs with the amount of available space for settlement. Many studies also show that algae and fast-growing filter feeders (mainly zoanthids and sponges) experience enhanced development in elevated nutrient conditions (Buss and Jackson, 1981; Goreau, 1992; Hallock et al., 1993; McCook, 1999; Holmes, 2000; Richter et al., 2001). A study of the boring sponge *Cliona celata* on coral reefs from the northern coast of Bahia (Reis and Leao, 2002) reveals that larger populations occur within a reef that previously was considered the most eutrophic in the region (Costa et al., 2000).

Another useful proxy for assessing the impacts of nutrient gradients in coral-reef systems is the distribution of chlorophyll *a*. The spatial variation of chlorophyll *a* in southern Bahia study sites (Fig. 2) is strongly correlated with nutrients (TON: $r = 0.801$, $p < 0.001$; SRP: $r = 0.735$, $p < 0.001$; DSI: $r = 0.806$, $p < 0.001$). These observations agree with reports from the literature that show nutrient-stressed coral-reef communities are dominated first by turf algae and then by increased numbers of planktonic producers (Smith et al., 1981; Twilley et al., 1985; D'Elia, 1986).

At the cellular level, nutrient enrichment can increase zooxanthellae density and chlorophyll content (Hoegh-Guldberg and Smith, 1989; Muscatine et al., 1989; Stambler et al., 1991; Dubinsky and Stambler, 1996). The photosynthetic rate per algal cell may be reduced under nutrient-rich conditions due to carbon limitation (Dubinsky et al., 1990), and most of the photosynthetically acquired carbon may be respired by growing algae instead of being translocated to the animal (Muscatine et al., 1989; Falkowski et al., 1993). Therefore, the functioning of the symbiosis between the zooxanthellae and their host gets disrupted. Some studies also report changes (increases and decreases) in both calcification and growth rates with nitrification. Kinsey and Domm (1974) measure a 50% decrease in community calcification following an 8-month fertilization period. Smith and Kinsey (1976) associate the low calcification rate with high phosphate concentrations. Negative effects on calcification and growth rates also have been observed where ammonium (Stambler et al., 1991; Ferrier-Pagès et al., 2000) and nitrate enrichments (Marubini and Davies, 1996) occur. However,

enhanced coral growth rates with high levels of nutrients have also been reported in several studies (Meyer and Schultz, 1985; Davies, 1990; Atkinson et al., 1995; Steven and Broadbent, 1997). In Brazil, research on the physiology of the coral–algal symbiosis has just begun, and so far, there is not enough data to support the contention that similar processes are occurring.

5. Seasonal patterns

Until recently, seasonal variability in the functioning of coral reefs has been overlooked because of the general perception that tropical communities lack season-to-season variability. Johannes et al. (1983) were the first to report that dissolved inorganic nitrogen (DIN) concentrations on coral reefs vary with the season. They also report that the uptake of nutrients by the benthic community is concentration-dependent.

In Brazilian reefs, the effect of the season is variable and significant for some parameters but not for others. Suspended solids, for example, are heavily influenced by season (see Fig. 4). Conversely, physical–chemical parameters (temperature, salinity, pH) are generally independent of seasonal effects; diel and tidal variations frequently are more important in controlling those parameters (Costa, 2002).

The seawater nutrient distribution is also significantly affected by season. On coral reefs from Porto Seguro Bay, southern Bahia, the higher nutrient concentration observed during the rainy season suggests that rainfall promotes an increasing load of nutrient inputs from terrigenous sources (runoff and groundwater seepage). This hypothesis is supported by a marked increase in nutrient concentrations near the bottom during the rainy season, notably for nitrogen (TON). This seasonal pattern suggests that submarine groundwater discharge (SGD) rather than regeneration from sediment bacterial activity may cause the elevated nutrient concentrations in the bottom layer. Such a pattern agrees with studies that focus on the effects of SGD in nearshore, and eventually offshore, communities (e.g. Lapointe and Clark, 1992; Lapointe et al., 1994).

The strong relationship between high precipitation and high coastal productivity rates suggests that land drainage and groundwater seepage are important factors in nutrient enrichment along the Bahian coast. Furthermore, the corresponding low salinities with high silicate levels implies that the freshwater is either river or groundwater derived (and not simply precipitation), which accords with findings from Cuet et al. (1988) and Bell (1992).

The seasonal increase in surface runoff and groundwater discharge has a clear effect in the nitrification of coastal areas, as measured by either nutrient or chlorophyll *a* concentrations (Costa et al., 2002). Such a pattern is also reflected in the biota, by means of a positive correlation with increased algae and zoanthid cover and a negative correlation with coral cover (Fig. 5).

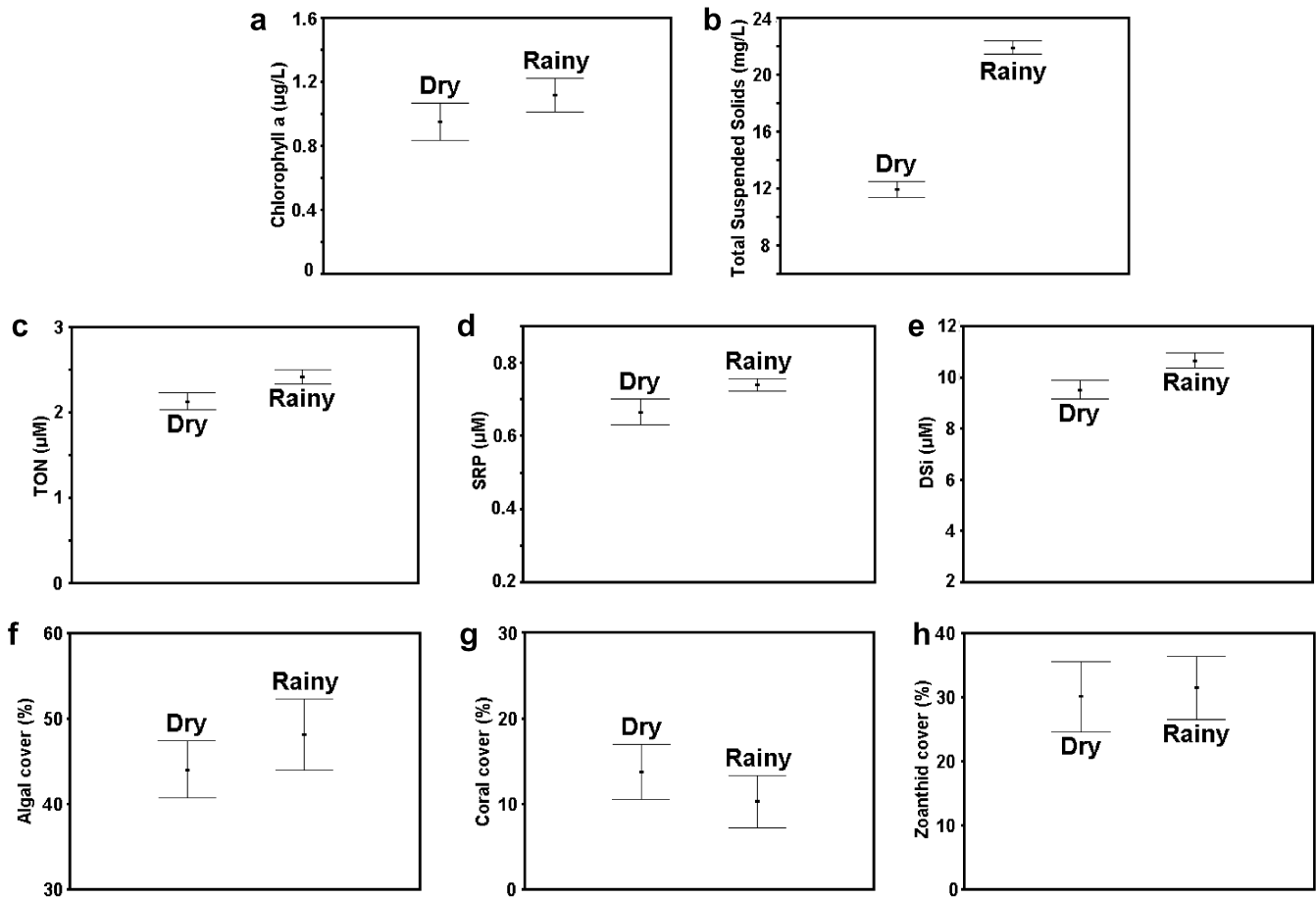


Fig. 4. Seasonal variation of parameters measured at the water column (a–e) and the major groups of benthic organisms (f–h) on nearshore reefs only at the study sites from southern Bahia, Brazil. Bars represent means and 95% confidence intervals. TON, total oxidised nitrogen; SRP, soluble reactive phosphorus; DSi, reactive silica.

These results also show that the statistical significance of the correlation between nutrients and algal cover is not as strong as that between nutrients and chlorophyll (Fig. 5), suggesting that fleshy and turf algae in the nearshore reefs may be nutrient replete; that is, they are not nutrient limited. Nutrient repletion of macroalgae has been previously reported (Koop et al., 2001).

6. Submarine groundwater discharge

Submarine groundwater discharge (SGD) is a relatively common phenomenon, recognized as an important source of nutrients to coastal waters (D'Elia et al., 1981; Sewell, 1982; Johannes and Hearn, 1985; Zimmermann et al., 1985; Oberdorfer et al., 1990; Valiela et al., 1990; Bugna et al., 1996; Cable et al., 1996a,b, 1997; Moore, 1999; Rutkowski et al., 1999). According to Johannes (1980), SGD occurs anywhere that an aquifer (water-bearing geological formation) connects hydraulically with the sea through permeable bottom sediments and the hydraulic head is above sea level. He also notes that in some areas, SGD can have greater ecological significance than surface runoff. In some areas, such as the west coast of the island

of Hawaii (Kay et al., 1977) and areas of the Yucatan Peninsula (Hanshaw and Back, 1980), virtually all freshwater entering the sea is in the form of submarine discharge. As groundwater moves through the subsurface, the concentration of nutrients may change due to biogeochemical interactions (Sansone et al., 1990). In certain areas, SGD can be a primary pathway for nutrients and contaminants to interact with overlying surface waters (Rutkowski et al., 1999). Lapointe et al. (1990) found significant groundwater inputs of nitrogen and dissolved organic phosphorus to canals and surface waters in the Florida Keys and suggested it may be a key factor initiating the phytoplankton blooms observed in that area.

Primary production in coastal environments is also affected by groundwater nutrient input, particularly in the case of nitrogen (Weiskel and Howes, 1992). Primary production that increases due to external sources of nutrients can lead to changes in species composition and in the rates of decay and energy flow (Valiela et al., 1990). The degree to which groundwater nutrients influence the coastal community depends on several interacting factors, including the amount of nutrient enrichment, the intensity of groundwater discharge to the area, hydrological fac-

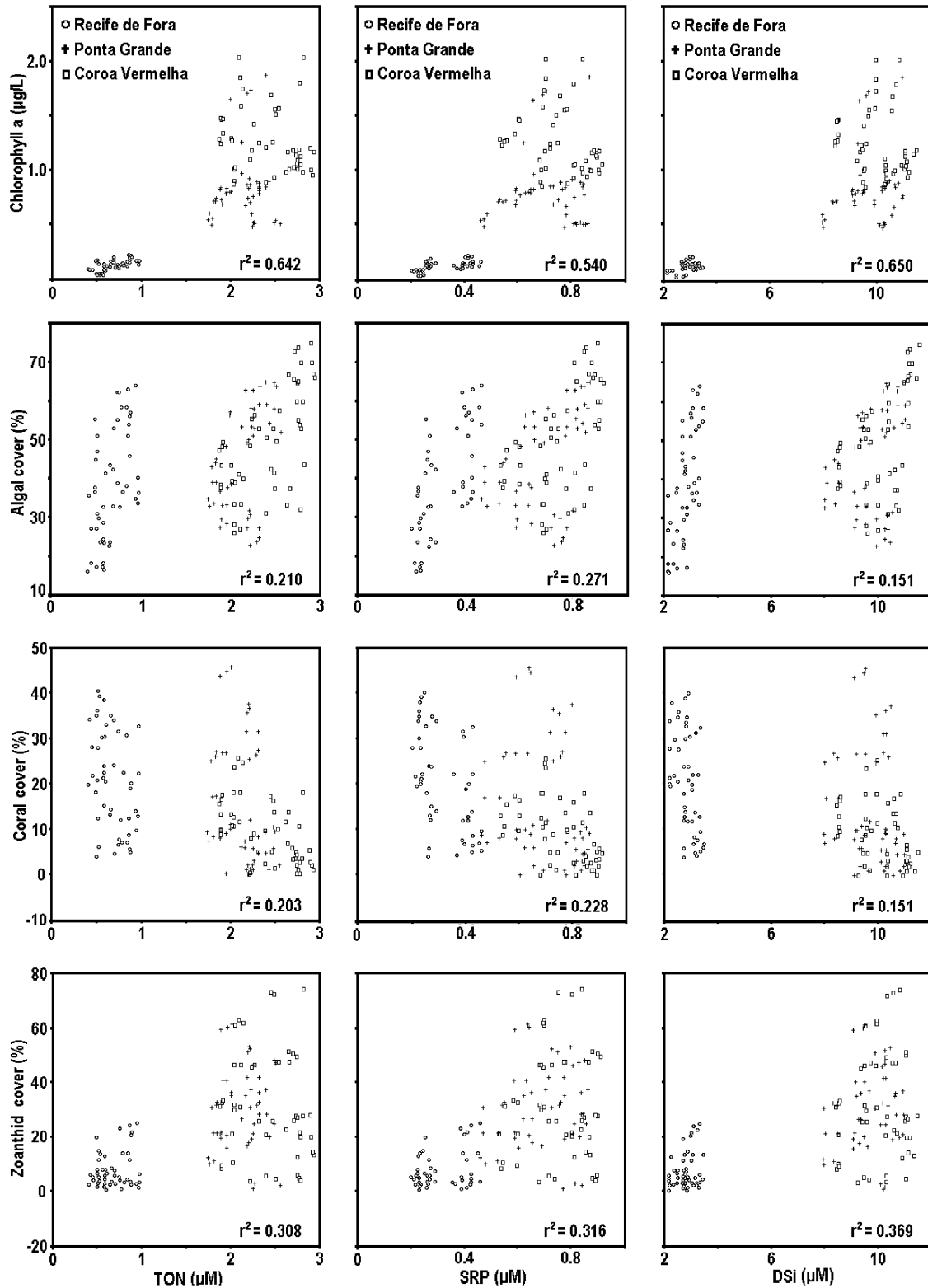


Fig. 5. Pearson's product-moment correlations between nutrients and chlorophyll *a*, algal, coral, and zoanthid cover in the study sites from southern Bahia, Brazil.

tors, porosity, and other sediment characteristics (Lapointe et al., 1990). Seasonality is also an important factor, because the flux of the SGD substantially increases during rainy seasons (Costa et al., 2000). The seasonal flux

of nutrients is determined by a combination of nutrient concentration and the intensity of submarine groundwater discharge during the time period (Rutkowski et al., 1999).

Reports of SGD in Brazil are scarce, but the research carried out so far indicates it is a quantitatively important component of the nutrient and water budget to coastal areas, especially near urban settlements. The first observation, in 1992, on a coastal lagoon near Rio de Janeiro City, derived from salinity and temperature profiles that revealed an intrusion of seawater to the lagoon through the porous sediments of a sand barrier (Costa and Zee, 1992). Subsequent topographic profiles also revealed that during high tides, the lagoon level was more than 1 m below sea level, allowing the inflow of seawater to the choked lagoon with very positive effects to its water quality.

Further studies of SGD performed in the north coast of Bahia (Costa et al., 2000) indicated that differences between lake and sea level can reach 5.9 m at low tides, generating a groundwater flux of approximately $45 \text{ L m}^{-2} \text{ day}^{-1}$ toward the coastal reefs. As a result of the widespread use of septic tanks and cesspits, groundwater nutrient concentration in the urbanized site is many times higher than that detected in the underdeveloped area. Nitrate concentrations vary between 0.41 and $1.68 \mu\text{M}$ in the latter and 5.75 and $8.03 \mu\text{M}$ in the former. Silicate concentrations, which along with salinity values can be used to mark groundwater discharge (Montaggioni et al., 1993), indicate that groundwater is likely to produce a significant input of terrestrial nutrients into the reef. With a flow rate of at least $20 \text{ L m}^{-2} \text{ day}^{-1}$, the SGD in the study area may constitute one of the main sources of nutrient-rich water to the coastal reefs of northern Bahia (Costa et al., 2000). Moreover, nutrient concentration behaves differently in different seasons, reflecting the role of rainfall in nutrient dilution and transport. Lower levels of ammonia and higher nitrate during the rainy season may suggest that a recharge of the permeable aquifer by oxygenated rainfall infiltration can allow increasing oxidation of ammonia to nitrite and then to nitrate.

Although the direction of the groundwater flow is assumed to oscillate as the fluctuating tides create differential heads between sea level and the water table, Costa et al. (2000) show this may not always be the case, and a unidirectional flow may be established. Such a permanent supply of nutrients via groundwater seepage may pose an ecological problem, leading to algal blooms and the steady deterioration of the water quality.

Another study reports coastal eutrophication driven by SGD in the south coast of Bahia and includes porewater nutrient analysis (Costa, 2002). Porewater TON concentrations are about twice the concentration in the overlying water column at the same locations. The data also suggest that the effect of the SGD is not restricted to nearshore reefs but may be an important factor controlling the differences between landward and seaward sides of the offshore reef. For this reef (located 8 km off the coast; Fig. 1), there was an overall increase of 27% in nutrient concentration from the dry to the rainy season, with the landward side alone experiencing an increase of 48% from the dry to the rainy season (Costa, 2002). Since the 1960s (Kohout,

1960) it has been accepted that the zone of diffusion (or mixing) may extend as far as 14 km seaward of the coast, which would allow groundwater discharge to have an impact well offshore. Moore (1999) refers to this subsurface region of mixing between meteoric water and seawater in coastal aquifers as “subterranean estuaries,” suggesting that water mixing in the subsurface creates an active chemical environment. In addition to these natural chemical processes, wastewater disposal in the urban area of Coroa Vermelha adds yet another source of water to the subsurface environment.

Significant flows of groundwater nutrients to coastal reefs also have been reported by Marsh (1977) in Guam, Johannes (1980) in Western Australia, Bienfang (1980) in Hawaii, D’Elia et al. (1981) and Lapointe (1997) in Jamaica, Lewis (1985) in Barbados, Jickels et al. (1989) in Bermuda, Naim (1993) in Reunion Island, Lapointe and Matzie (1996) in the Florida Keys, and Vacelet et al. (1998) in the Comoro Archipelago.

7. Implications of nitrification for coastal resources management

The rate of biologically available nutrient supply to aquatic systems has greatly increased with time through human activity. The magnitude of that increase, however, is poorly known (Conley, 2000). In heavily industrialized countries, most management plans for reducing nutrient loads are on the order of a 50–80% reduction of present loads (Boynton et al., 1995). The construction and implementation of advanced wastewater treatment plants are an important component of such reduction, especially for P (Conley, 2000). In Brazil however, the condition of wastewater treatment and disposal services is critical. Almost half of the districts in the country (48%) do not have any kind of service, and only 20% undertake wastewater treatment (IBGE, 2002). Fortunately, most coral-reef formations along the coast, from the State of Maranhão to south of Bahia, occur where urban development is still incipient (Leão and Dominguez, 2000). It is therefore urgent to perform baseline studies of biodiversity in these areas, along with nutrient budgets and careful urban planning.

Because nutrient enrichment and sedimentation are the main effects of river runoff, managers should target land use practices along the rivers. One such initiative is to encourage the preservation of mangrove areas along the river margins and especially in estuaries, where they are relentlessly being cut for pier construction and land development.

Another important measure would be to regulate fisheries in coral-reef areas, because algal takeover of coral-reef communities is promoted not only by increasing nutrient flux but also by the declining herbivore population. Legal protection and/or restoration of herbivore population (especially herbivorous fish) must be considered, perhaps through better enforcement of marine protected area

(MPA) regulations in park areas, as well as the creation of new MPAs and extensions of parks already established to include other reef areas.

7.1. Community involvement

Marine protected areas have a significant role to play in protecting key sites and raising consciousness of the need for and benefits of marine conservation. The fishing community must be included in the process, and to this end, an environmental education campaign should be established. In addition, securing community support for MPAs will require the development of management plans that are compatible with traditional practices for the use and conservation of the marine resources. These traditional practices may include the right to fish, the right of access and passage, and the right to use stretches of the reef as a landing place. Cooperation with local communities is most likely if it can be shown that it is in the interest of local people to establish and manage the MPAs.

In parallel with these initiatives, alternative means of subsistence should be provided (e.g., aquaculture) to gain the full participation of the fishing community. Coastal programs that have had some degree of success have managed to bring about income generation (Yap, 2001). Providing opportunities for sustainable development and demonstrating that sustainable benefits will flow from the management of resources is fundamental to secure community cooperation.

7.2. Building capacity

Acceptance of the need for protected areas and broader management strategies appears to be growing, but its realization depends on human resources to implement the plans and strategies. Increased funding, strong institutional support, and specifically tailored control measures will be ineffective unless a pool of personnel trained in protected area development and management expands rapidly. Therefore, training and capacity building are fundamental requirements for managing marine resources on a sustainable basis.

7.3. Monitoring program

After a management plan is in place, it is necessary to evaluate the effect and effectiveness of that plan. To this end, monitoring programs should be established and conducted. This monitoring should be capable of distinguishing between natural and human-induced effects and determining trends over time. Evaluating the occurrence and magnitude of trends requires a commitment to long-term monitoring (multiple years) and consistent data collection throughout a network of sites that represent the target population. In addition, it should:

- (1) Be built on a foundation of existing successful “key-stone” environmental monitoring and research programs to allow comparisons and evaluations of long-term trends.
- (2) Be cost efficient and provide the best possible sound results with available resources. To accomplish this goal, a careful selection of methods and techniques for both sampling and statistical treatment is necessary, and a pilot study should be undertaken before any definition to test the adequacy of the chosen protocols.
- (3) Adapt to evolve and innovate as new and improved methodologies come into place, without losing the value of historical data sets.
- (4) Allow timely data accessibility to federal and state agencies, other public organisations, and the private sector, thus providing technical and educational support for the establishment of relevant policies and protective measures.

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Appendix A

Nutrification. vs. eutrophication: Is there a difference?

The literal meaning of the word eutrophication is “well-nourished.” A concept largely used in limnology to explain the process by which lakes gradually age and become more productive, it is characterized by a geologically slow shift from in-lake biological production driven by allochthonous (external to the water body) loading of nutrients to production driven by autochthonous (in-lake) processes (Rast and Thornton, 1996). This shift typically is accompanied by changes in species and biotic community composition as the aquatic ecosystem ultimately is transformed into a terrestrial biome. This process is also called natural eutrophication and normally takes thousands of years to develop.

This typically slow, natural process can be greatly accelerated by human interference in the biogeochemical cycling of nutrients within a watershed; the resulting cultural eutrophication can create inimical conditions to the continued use of the water body for human-driven economic and

recreational purposes. Excessive algal and rooted plant growth, degraded water quality, extensive deoxygenation of the bottom-water layers, and increased fish biomass accompanied by decreased harvest quality are some features of this process (Rast and Thornton, 1996). Therefore, cultural or anthropogenic eutrophication may result in water quality deterioration caused by excessive plant nutrients from anthropogenic sources (Havens et al., 1996).

Anthropogenic nutrient sources can be broadly segregated into two categories: readily identifiable point sources (e.g., sewage effluents) and diffuse (or non-point) sources (e.g., runoff from agricultural land, urban lawns, golf courses, or atmospheric sources), with the relative contribution of each varying between catchments (Environment Agency, 1998). In both examples, phosphorus is typically the key nutrient controlling eutrophication (Campbell, 1994; Sharpley et al., 1999), and sewage was the main source of phosphorus to lakes when detergents contained large quantities of polyphosphates.

Many studies dealing with nutrient enrichment of coastal and marine waters use the word “eutrophication.” This apparent confusion does not consider fundamental differences among marine, freshwater, and brackish water systems. In streams, lakes, lagoons, and estuaries, one of the main consequences of eutrophication is a seasonal high peak of biological oxygen demand (BOD), which leads to seasonally depleted oxygen levels (<2 mg/L) (Diaz and Rosenberg, 1995). Most aquatic species cannot survive at such low oxygen levels, and fish kills are common features in eutrophic areas.

This oxygen depletion is commonly referred to as hypoxia (Diaz and Rosenberg, 1995; Rabalais et al., 2001). In marine environments, however, only extreme nutrient-enrichment events, coupled with small tidal mixing, can lead to the oxygen depletion typical of eutrophication processes. Nevertheless, the benthic community structure can drastically change in conditions of even slight nutrient enrichment (Bell, 1992; Lapointe, 1997). To avoid coral reef nutrification, biologically available nitrogen (nitrate plus ammonia) must be below 1.0 μM (less than 0.014 parts per million of nitrogen), and biologically available phosphorus (orthophosphate plus dissolved organic phosphorus) must be below 0.1 μM (less than 0.003 parts per million of phosphorus). In addition, concentrations of chlorophyll need to be below 0.5 parts per billion (Bell, 1992; Lapointe, 1997).

Another difference between the eutrophication of terrestrial and marine waters is that phosphorus is the nutrient limiting eutrophication in standing/running waters and some estuaries (Jickels et al., 1989; Sharpley et al., 1999), whereas nitrogen is the primary growth-limiting element in marine systems (D’Elia and Wiebe, 1990; Nixon et al., 1996). Therefore, some scientists prefer to call the process of nutrient enrichment of coral reefs “nutrification” if such enrichment is not eutrophication in the sense of substantially increasing BOD and does not imply enrichment with organic carbon (Kinsey, 1991; Hallock et al., 1993; Szmant and Forrester, 1996).

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