

Chapter XX

Coastal eutrophication in Brazil: The role of nutrient excess on coral reef demise, with special reference to Bahian reefs

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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 twenty years. Many coral reefs worldwide have suffered an extensive decline in coral diversity and density, with increasing cover of noncoralline, fleshy and filamentous macroalgae (Done, 1992; Wilkinson, 1992; Hughes, 1994; McCook, 1999; Hughes *et al.*, 1999). Various disturbances have been invoked to explain this change, including storms (Knowlton *et al.*, 1981; Rogers *et al.*, 1991; Blair *et al.*, 1994; Ostrander *et al.*, 2000), coral bleaching (Williams & Bunkley-Williams, 1990; Meesters & Bak, 1993; Brown *et al.*, 1994; Glynn, 1996), sedimentation (Rogers, 1990; Cortés, 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.*, 1997; Aronson & Precht, 2000) and eutrophication (Hallock & Schlager, 1986; Tomascik & Sander, 1987; Hunte & 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 or the effects of tourism) – see for instance the works of Kinsey (1988), Connell (1997) and Connell *et al.* (1997). These authors noted that coral reefs recover quite rapidly from acute stresses. Chronic stresses however, have an intense and prolonged impact by destabilising the community structure on the reef, and may also inhibit coral recovery after destructive events. For instance, Bythell *et al.* (2000) observed that reef sites destroyed by disease in the 1970s are showing little or no recovery, while sites less than a kilometre away that were devastated by Hurricane Hugo in 1989 are recovering well.

As the Brazilian coast is not affected by hurricanes, nor has it experienced infestations of COTS (crown-of-thorns starfish) or other predators, the reefs were spared from natural acute stresses that have key influence on Caribbean and Indo-Pacific areas. Moreover, there are no reports of diseases in Brazilian corals and bleaching events normally present recovery rates above two-thirds (Migotto, 1997; Castro & Pires, 1999). Therefore, although sea level variations during the last 8000 years has played an important role in defining reef structure and morphology (Leão, 1982), all major stresses to the Brazilian reefs are related to human activities. These include sedimentation caused by up-stream land practises and extensive logging of Brazil's Atlantic coastal forest (Addad & Martins-Neto, 2000; Werner *et al.*, 2000), overfishing (Rocha, 1997), tourism related activities (Leão, 1996) and nutrient enrichment or nutrification (Costa *et al.*, 2000).

The purpose of this article is to review the current state of knowledge of coastal nutrification in Brazil, with special reference to the coral reef areas of the Bahia State. It also includes a comparison of the available dataset for Brazil with other coral reef areas worldwide, and a

discussion of the major research findings regarding nitrification processes and effects, and its application to the Brazilian reefs. The final section also provides some recommendations for the management of coastal resources in Brazil.

2. Nitrification and coral reefs

Although there is a growing recognition that reefs are not limited to oligotrophic environments (see, for instance, the reviews from Hatcher, 1997, and Szmant, 1997), there is also an established consensus that in healthy coral reefs the biological activity in the plankton community is trivial relative to the benthos. Margalef (1968) was one of the first to point out the scarcity of hermatypic (reef-building) corals in high-nutrient environments. Since then, the nutrient fluxes that support the productivity of coral reefs have produced a vast numbers of studies on reef ecology and biogeochemistry (see for instance, D'Elia, 1977, 1988; Andrews & Gentien, 1982; Crossland, 1983; Entsch *et al.*, 1983; Davies, 1984; Hallock & Schlager, 1986; Atkinson, 1988; Sorokin, 1990; Bell, 1992; Delgado & Lapointe, 1994; Hoegh-Guldberg *et al.*, 1997; Lapointe, 1997; Charpy *et al.*, 1998; Larned, 1998; Ferrier-Pagès *et al.*, 2000; Costa, 2001).

Agriculture and urban activities are major sources of phosphorus and nitrogen to aquatic ecosystems. Atmospheric deposition further contributes as a source of N. These nonpoint inputs of nutrients are difficult to measure and regulate because they derive from activities dispersed over wide areas of land and are variable in time due to the effects of weather (Carpenter *et al.*, 1998). In coral reef ecosystems, nitrification (see Box 20.1) can introduce an imbalance in the exchange of nutrients between the zooxanthellae (the symbiotic algae) and the host coral (Hoegh-Guldberg & 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 & Velimirov, 1991; Genin *et al.*, 1995), and may

enhance algal growth and the proliferation of seaweeds. The latter rapidly outgrow, smother and eventually replace, the slow-growing coral reef, adapted to cope with the low nutrient concentrations typical in tropical seas. Coral larvae settlement is also prevented (or diminished) with an increase of the plankton community density and the probability of coral larval survival declines when other plankton, especially carnivorous species, are abundant (Birkeland, 1977; Harrison & Wallace, 1990; Hunte & Wittenberg, 1992). Nutrification seriously degrades aquatic ecosystems and impairs the use of water for drinking, industry, agriculture, recreation, and other purposes (Carpenter *et al.*, 1998).

3. Nutrification in the Brazilian coast

Flowing down from the equator, waters from the oceanic Brazil Current induce oligotrophic and near to homogeneous conditions of the chemical constituents along the inner shelf (Koenig & 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 & Lara, 2001) or upwelling processes (Carbonel & Valentin, 1999; Gonzalez-Rodriguez, 1999). Estuarine and coastal areas near to major urban settlements are the most eutrophic (Contador & Paranhos, 1996; Jorcin, 2000), with untreated sewage discharge being one of the main sources of nutrients to coastal areas (Kjerfve *et al.*, 1997; Carreira & Wagener, 1998).

Land impacts upon offshore reefs are mitigated due to the efficient flushing by the Brazil Current (Knoppers *et al.*, 1999). Nearshore reefs, however, are subjected to the influence of a highly siliciclastic sediment influx (Leão, 1996) and receive substantial supplies of nutrients from terrigenous sources such as runoff, river discharge and groundwater inputs (Costa *et al.*, 2000). At these coastal reefs, the highest levels of water-column productivity and benthic algae cover were observed. For example, Metzler *et al.* (1997) report 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 $\mu\text{g/L}$ in the oceanic region. Costa (2001) found a similar pattern around the reefs of Porto Seguro Bay, Bahia State, with the offshore reef (Recife de Fora - RF) having a quarter of the chlorophyll *a* concentrations and a third of the suspended solids concentrations compared to those encountered at the nearshore reefs (Fig. 20.1). Differences between the two nearshore reefs, Coroa Vermelha (CV) and Ponta Grande (PG), reflect the varying degree of urbanization, with the concentration gradients being related to distance from a localized source of pollution (an urban settlement without sewerage treatment in Coroa Vermelha), 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 (rivers, mangroves and grass-bed detritus) and anthropogenic (wastewater seepage and agricultural run-off). Metzler *et al.* (1997) found that, in oceanic waters, NO_3^- was the main form of nitrogen available for phytoplankton (64-86% of total nitrogen), whilst at the inshore station, NO_3^- represented less than 32% of the total nitrogen supply. Nonetheless, primary production was dominated by regenerated production, which relies on the recycling of nutrients within the photic zone, the benthos being the major source of nutrients to recycling. Uptake of reduced forms of nitrogen represented 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 was also observed in southern Bahia, with total oxidized nitrogen ($\text{TON} = \text{NO}_3^- + \text{NO}_2^-$) concentrations in the nearshore reefs varying from 1.74 μM to 2.81 μM during the dry season, and from 1.95 μM to 3.64 μM during the rainy season, whilst the offshore reef presented TON concentrations varying from 0.41 μM to 0.89 μM during the dry season, and from 0.52 μM to 1.16 μM during the rainy season (Costa, 2001). Similar patterns were observed in soluble reactive phosphorus (SRP)

and reactive silica (DSi) concentrations, and were negatively correlated with coral cover ($p < 0.05$), as can be seen in Fig. 20.2 and Table 20.1. Such a correlation suggests that an adverse effect of nutrients may be occurring, especially because this gradient was positively correlated with percent cover of both algae and zoanthids ($p < 0.05$).

Coroa Vermelha also showed the most elevated nutrient concentrations from all study sites (Fig. 20.2), and this is 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 in Brazilian coral reefs

There has been considerable discussion and some controversy among scientists and conservationists regarding the 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 a large number of studies that observed stimulation of primary production with increased nutrient concentrations (Kinsey & Domm, 1974; Weiss & Goddard, 1977; Smith *et al.*, 1981; Hatcher & Larkum, 1983; Lapointe, 1985; Tomascik & Sander, 1985, 1987; Cuet *et al.*, 1988; Kinsey, 1988; Lapointe & O'Connell, 1989; Littler *et al.*, 1991; Bell, 1992; Lapointe *et al.*, 1993; Littler *et al.*, 1993; Naim, 1993; Delgado & Lapointe, 1994; Lapointe *et al.*, 1994; Lapointe, 1997; Adey, 1998; Larned, 1998).

This assumption, however, has been challenged by recent studies (Grigg, 1994, 1995; Larkum & Koop, 1997; Miller *et al.*, 1999; Koop *et al.*, 2001), which have demonstrated that algal communities in some reef areas may be nutrient replete, and that additions of inorganic nutrients will not necessarily increase algal accumulation. They suggest that 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 fact that increasing nutrification may increase algal growth and primary productivity but that this will happen only when growth is limited by 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, as the municipal sewage collection and treatment systems are frequently inadequate or even non-existent. Some of the 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 groundwaters by infiltration through highly porous sandstone and beach rocks (Costa *et al.*, 2000). Such nutrient-enriched groundwaters discharge into shallow nearshore waters, resulting in coastal eutrophication. As a measure of the problem, from the 812 districts in the Bahia State (the most extensive coastline in the country, 830-km long), only 282 has sewage collection system, from which only 51 (6.3%) has any kind of treatment, before being flushed to the rivers, estuaries and coastal areas (IBGE, 2002).

There are several ways by which 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 between algae and corals. The dataset derived from the southern Bahia study has indicated that coral cover increase presented 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, 2001).

Other fast-growing organisms can have a competitive edge over corals when the nutrient supply is increased. This is the case for zoanthids, especially the genus *Palythoa*, which are the organisms most adapted to take advantage of an increase in nutrient concentrations in coastal areas (Costa, 2001). On nearshore reefs, there was a negative correlation between zoanthid and algal abundance and a positive correlation with the amount of available space for settlement. Many studies have also shown that algae and fast growing filter feeders (mainly zoanthids and sponges) have their development enhanced in elevated nutrient conditions (Buss & 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 *et al.*, 2001) revealed that larger populations occur at a reef previously considered the most eutrophic in the region (Costa *et al.*, 2000).

Another useful proxy for assessing the impacts of nutrification gradients in coral reef systems is the distribution of chlorophyll *a*. The spatial variation of chlorophyll *a* in southern Bahia study sites (Fig. 20.1) was found to be 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 are in agreement with reports from the literature, which show that nutrient-stressed coral-reef communities are firstly dominated 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 lead to an increase in zooxanthellae density and chlorophyll content (Hoegh-Guldberg & Smith, 1989; Muscatine *et al.*, 1989; Stambler *et al.*, 1991; Dubinsky & Stambler, 1996). It has been suggested that the photosynthetic rate per algal cell is reduced under nutrient-rich conditions, due to carbon limitation (Dubinsky *et al.*,

1990), and that most of the photosynthetically acquired carbon is respired by the 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 is disrupted. Some studies have also reported changes (increase and decrease) in both calcification and growth rates with nutrification. Kinsey & Domm (1974) measured a decrease of 50% in community calcification following an 8-month fertilization period. Smith & Kinsey (1976) associated the low calcification rate to high phosphate concentrations. Negative effects on calcification and growth rates were also observed under ammonium (Stambler *et al.*, 1991; Ferrier-Pagès *et al.*, 2000) and nitrate enrichments (Marubini & Davies, 1996). However, enhancement of coral growth rates under high levels of nutrients has also been reported in several studies (Meyer & Schultz, 1985; Davies, 1990; Atkinson *et al.*, 1995; Steven & Broadbent, 1997). In Brazil, research on the physiology of the coral-algae 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 function 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 varied with season. They also reported that the uptake of nutrients by the benthic community was concentration-dependent.

In Brazilian reefs, the effect of season is variable, being significant for some parameters and not for others (see Fig. 20.3). Suspended solids, for instance, is one variable heavily influenced by season. Conversely, the physical-chemical parameters (temperature, salinity,

pH) are generally independent of seasonal effects, with diel and tidal variations being frequently more important (Costa, 2001).

The seawater nutrient distribution is also significantly affected by season. On coral reefs of Porto Seguro Bay, southern Bahia, the observed higher nutrient concentration during the rainy season suggests that rainfall promote an increasing load of nutrient inputs from terrigenous sources (run-off and groundwater seepage). This hypothesis is supported by a marked increase in nutrient concentrations near the sediment during the rainy season, notably for nitrogen (TON). This seasonal pattern suggests that submarine groundwater discharge (SGD) rather than regeneration from the sediment, may be the cause of the elevated nutrient concentrations in the bottom layer. Such pattern is in agreement with some recent studies focusing in the SGD affecting nearshore, and eventually offshore, communities (e.g. Lapointe & 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 is an indicator that the freshwater is either river or groundwater derived (and not simply precipitation), which is in accordance 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. Such 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. 20.4).

These results also shown that the statistical significance of the correlation between nutrients and algae cover is not as strong as that between nutrients and chlorophyll (Fig. 20.4), suggesting that fleshy and turf algae in the nearshore reefs may be nutrient replete, i.e. they are not nutrient limited. Nutrient repletion of macroalgae has been previously reported (Koop *et al.*, 2001).

6. The Submarine Groundwater Discharge

Submarine groundwater discharge (SGD) is a relatively common phenomenon and has been recognized as an important source of nutrients to coastal waters (D'Elia *et al.*, 1981; Sewell, 1982; Johannes & 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, 1996, 1999; Rutkowski *et al.*, 1999). According to Johannes (1980), a SGD occurs anywhere that an aquifer (water-bearing geological formation) is connected hydraulically with the sea through permeable bottom sediments and the head is above sea level. He also pointed out that, in some areas, SGD can have greater ecological significance than surface runoff. Indeed, there are some areas, such as the west coast of the island of Hawaii (Kay *et al.*, 1977) and areas of the Yucatan Peninsula (Hanshaw & Back, 1980), where 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 one of the primary pathways 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 this may be a key factor for 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 & Howes, 1992). Primary production that is increased 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 factors, porosity, and other sediment characteristics (Lapointe *et al.*, 1990). Seasonality is also an important factor, as the flux of the SGD is substantially increased during rainy seasons (Costa *et al.*, 2000). The seasonal flux of nutrients is determined by a combination of nutrient concentrations 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 have indicated that it is a quantitatively important component of the nutrient and water budget to coastal areas, especially near urban settlements. The first observation was made in 1992, on a coastal lagoon near Rio de Janeiro City. Salinity and temperature profiles revealed an intrusion of seawater to the lagoon through the porous sediments of a sand barrier (Costa & Zee, 1992). Subsequent topographic profiles also revealed that, during high tides, the lagoon level occurred at more than 1m below the sea level, thus allowing the inflow of seawater to the choked lagoon with very positive effects to its water quality.

Further studies of SGD were also performed in the north coast of Bahia (Costa *et al.*, 2000). The data has shown that differences between lake and sea level can reach 5.9m at low tides, generating a groundwater flux of approximately $45 \text{ litres.m}^{-2}.\text{day}^{-1}$ towards the coastal reefs. Due to the widespread use of septic tanks and cesspits, groundwater nutrient concentration in the urbanized site was many times higher than those detected in the underdeveloped area.

Nitrate concentrations varied between 0.41 and 1.68 μM in the latter, and from 5.75 to 8.03 μM in the former. Silicate concentrations, which along with salinity values can be used as a marker of groundwater discharge (Montaggioni *et al.*, 1993), indicated that groundwater was likely to produce a significant input of terrestrial nutrients onto the reef. With a flow rate of at least 20 litres.m⁻².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 also behaved distinctly between seasons, reflecting the role of rainfall in nutrient dilution and transport. Lower levels of ammonia and higher nitrate found during the rainy season may suggest that a recharge of the permeable aquifer by oxygenated rainfall infiltration can allow an 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 a differential head between sea level and the water table, the study of Costa *et al.* (2000) has shown that 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 deterioration of the water quality.

Another study that reported coastal eutrophication driven by SGD was undertaken in the south coast of Bahia and included porewater nutrient analysis (Costa, 2001). Porewater TON concentrations were about twice the concentration in the overlying water column at the same locations. The data also suggested that the effect of the SGD was not restricted to the nearshore reefs, and may be an important factor controlling the differences between landward and seaward sides of the offshore reef. This reef (located 8 km off the coast – see Fig. 20.1) observed an overall increase of 27% in nutrient concentration from dry to rainy season, with the landward side alone experiencing an increase of 48% from dry to rainy season (Costa, 2001). Since the sixties (Kohout, 1960) it is accepted that the zone of diffusion (or mixing)

may be as much as 14 km seaward of the coast, thus allowing groundwater discharge to have an impact well offshore. Moore (1999) referred to this subsurface region of mixing between meteoric water and seawater in coastal aquifers as "subterranean estuaries", suggesting that the mixing of these waters 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 were also 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, Jickells *et al.* (1989) in Bermuda, Naim (1993) in Reunion Island, Lapointe & Matzie (1996) in Florida Keys, and Vacelet *et al.* (1998) in Comoro Archipelago.

7. Implications of nutrification 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 in the order of 50% to 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 that 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 (47.8%) do not have any kind of service, and only 20.2% undertakes wastewater treatment (IBGE, 2002). Fortunately, most coral reef formations along the coast, from the State of Maranhão to the south of Bahia, occur in areas where urban development is still incipient (Leão & Dominguez, 2000). It is therefore urgent to perform

baseline studies of biodiversity in these areas, along with nutrient budgets and careful urban planning.

Since nutrient enrichment and sedimentation are the main effects of river runoff, managers should also target land use practises along the rivers. One such initiative is to encourage the preservation of mangrove areas along the river margins and especially in estuaries, as they are relentlessly being cut for pier constructions and land claims.

Another important measure would be to regulate the fishery in coral reef areas, as algal takeover of coral-reef communities is promoted not only by increasing nutrient flux, but also by declining herbivore populations. Legal protection and/or restoration of herbivore populations (especially herbivorous fish) must also be considered. This may be achieved by better enforcement of MPA regulations in park areas, as well as by creation of new MPAs and by extending the parks already established to include other reef areas.

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. Additionally, securing community support for MPAs will require the development of management plans that are compatible with traditional practises for the use and conservation of the marine resources. These traditional practises may include, to some extent, the right to fish, the right of access and passage, and the right to use stretches of the reef as a landing place. Co-operation with local communities is most likely to be achieved where it can be shown that it is in the interest of local people to establish and manage the MPAs.

In parallel to these initiatives, alternative means of subsistence should be provided (aquaculture being a suitable option) in order to guarantee the full participation of the fishing community. Coastal programs that have had some degree of success are those that have managed to bring about income generation (Yap, 2001). Providing opportunities for sustainable development, and demonstrating that sustainable benefits will flow from management of resources, is fundamental to secure community co-operation.

Building capacity

Acceptance of the need for protected areas and broader management strategies appears to be growing but its realization depends upon 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 trained personnel for protected area development and management expands rapidly. Therefore, training and capability building are fundamental requirements for enabling marine resources to be managed on a sustainable basis.

Monitoring program

Once 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 also capable of distinguish between natural and human-induced effects and to determine trends over time. Evaluating the occurrence and magnitude of trends requires a commitment to long-term monitoring (multiple years), and consistent data collection through a networks of sites that represent the target population. In addition it should:

- a) Be built on a foundation of existing successful 'keystone' environmental monitoring and research programs, in order to allow inter-comparisons and evaluation of long-term trends.
- b) Be cost efficient, by providing the best possible sound results with the available resources. In order to accomplish that 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 is made, in order to test the adequacy of the chosen protocols.
- c) Be adaptive so it can evolve and innovate, as new and improved methodologies come into place, without losing the value of historical data sets.
- d) Allow timely data accessibility to federal and state agencies, other public organisations, and the private sector, providing technical and educational support for the establishment of relevant policies and protective measures.

Box 20.1. Nutrification vs. Eutrophication: Is there a difference?

The literal meaning of the word eutrophication is "well-nourished". It is 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 & Thornton, 1996). This shift typically is accompanied by changes in species and biotic community composition, as an aquatic ecosystem is ultimately transformed into a terrestrial biome. This process is also called *natural eutrophication* and it normally takes thousands of years to progress.

However, this typically slow process can be greatly accelerated by human intervention in the natural 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

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 & 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 (such as sewage effluents), and diffuse (or non-point) sources (such as the run-off 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 in controlling eutrophication (Campbell, 1994; Sharpley *et al.*, 1999), sewage being the main source of phosphorus to lakes when detergents contained large quantities of polyphosphates.

There is, however, a broader definition of eutrophication that allows its use in coastal and marine ecosystems. For instance, the definition of eutrophication adopted by the England and Wales Environment Agency (Environment Agency, 1998) is: "*The enrichment of waters by inorganic plant nutrients (primarily phosphorus, nitrogen, and carbon) which results in the stimulation of an array of symptomatic changes. These include the increased production of algae and/or other aquatic plants, affecting the quality of the water and disturbing the balance of organisms present within it. Such changes may be undesirable and interfere with water uses*".

Many studies dealing with nutrient enrichment of coastal and marine waters have also used the word "eutrophication". This apparent confusion does not consider a fundamental difference between the marine, freshwater and brackish water systems. In streams, lakes, lagoons and estuaries, one of the main consequences of eutrophication is the seasonal high peak of biological oxygen demand (BOD) which leads to seasonally-depleted oxygen levels (< 2mg/L) (Diaz & 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 & Rosenberg, 1995; Rabalais *et al.*, 2001). In marine environments including coral reefs, however, only extreme nutrient-enrichment events, coupled with small tidal mixing, can lead to the oxygen depletion typical of eutrophication processes. Benthic community structure, however, can change radically under conditions of even slight nutrient enrichment (Bell, 1992; Lapointe, 1997). To avoid coral reef eutrophication, biologically available nitrogen (nitrate plus ammonia) needs to be below 1.0 μM (less than 0.014 parts per million of nitrogen), and biologically available phosphorus (orthophosphate plus dissolved organic phosphorus) needs to 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 (Jickells *et al.*, 1989; Sharpley *et al.*, 1999), whilst nitrogen is the primary growth-limiting element in marine systems (D'Elia & Wiebe, 1990; Nixon *et al.*, 1996). Owing to these differences, some scientists prefer to call the process of nutrient-enrichment of coral reefs "eutrophication", once 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 & Forrester, 1996).

8. References

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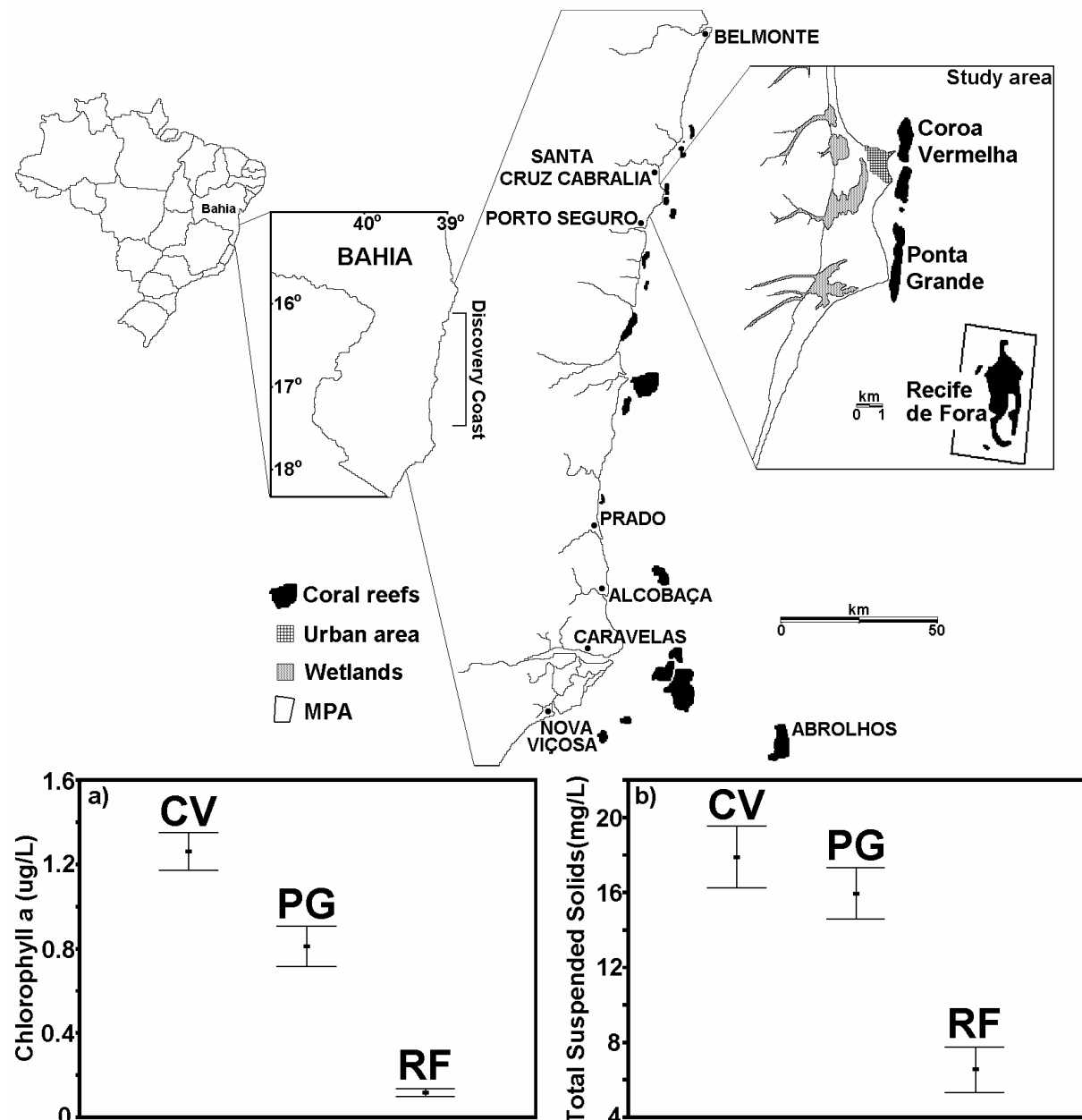


Figure 20.1. Spatial variation of chlorophyll *a* and TSS concentrations measured at the water column in the study sites from southern Bahia, Brazil. Bars represent mean and 95% confidence intervals.

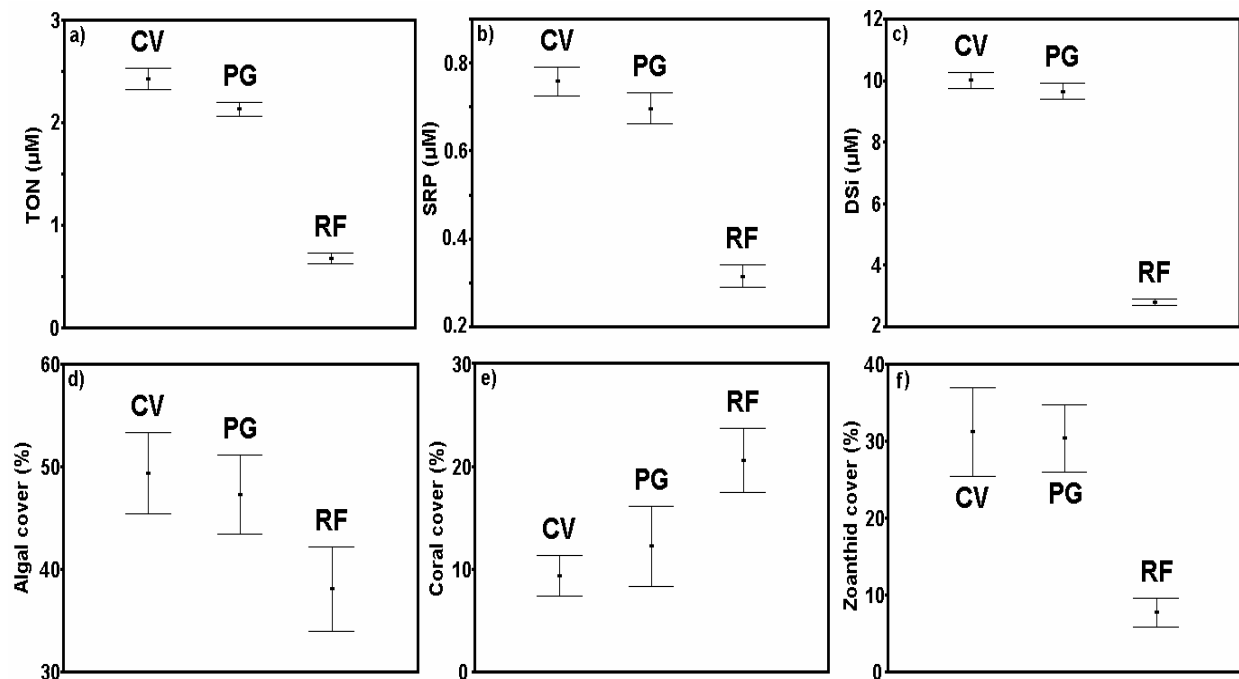


Figure 20.2. Spatial variation of nutrient concentration measured at the water column (a-c) and the major groups of benthic organisms (d-f) in the study sites from southern Bahia, Brazil. Algal cover includes fleshy, turf and coralline algae. Coral cover includes stony corals and hydrocorals. Bars represent mean and 95% confidence intervals. TON = total oxidised nitrogen, SRP = soluble reactive phosphorus, DSi = reactive silica

Table 20.1. Pearson's product-moment correlation between measured parameters in the study sites from southern Bahia, Brazil. TON = total oxidised nitrogen, SRP = soluble reactive phosphorus, DSi = reactive silica

| | Chl a | 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 |

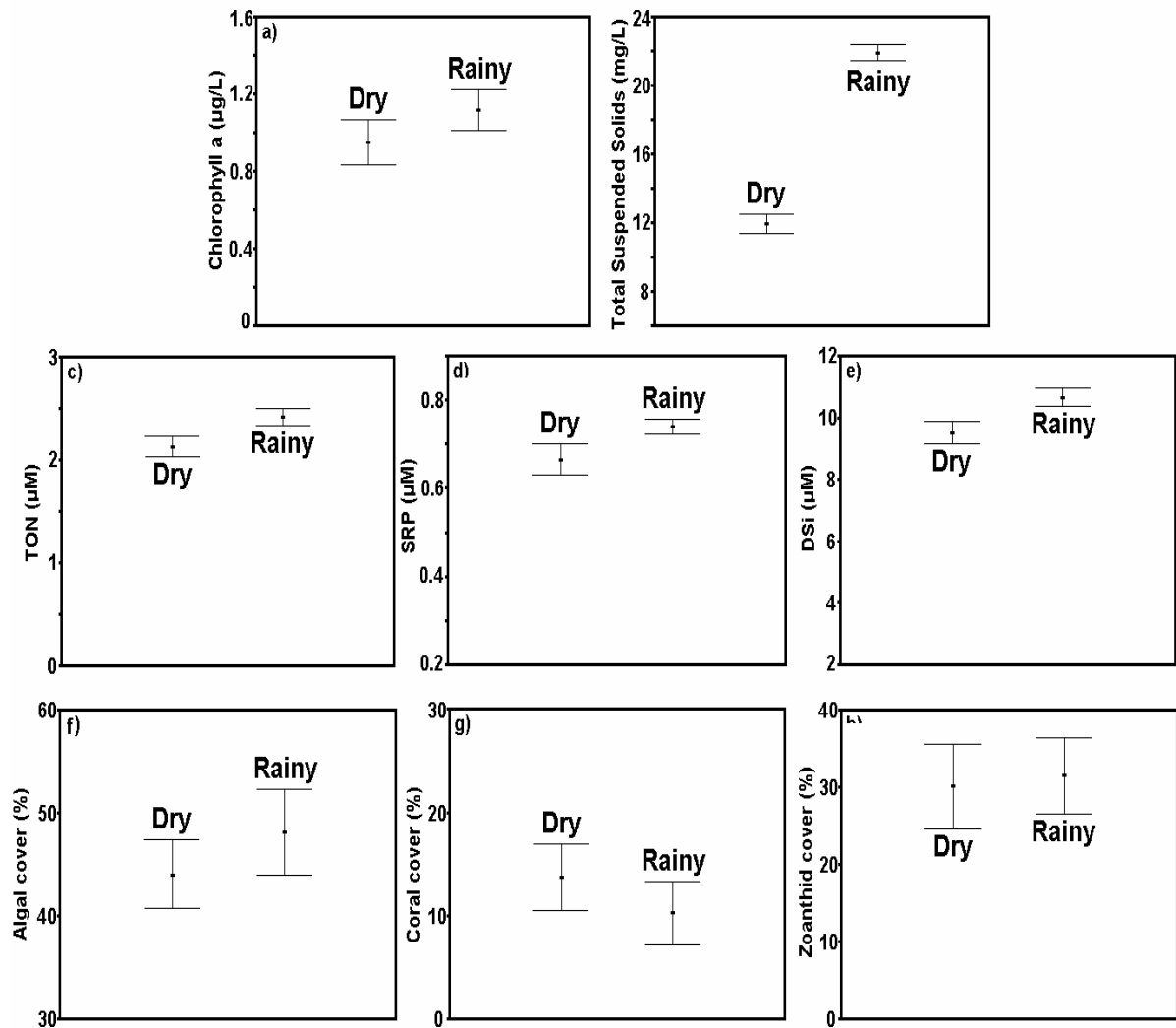


Figure 20.3. Seasonal variation of parameters measured at the water column (a-e) and the major groups of benthic organisms (f-h), on nearshore reefs only, at the study sites from southern Bahia, Brazil. Bars represent mean and 95% confidence intervals. TON = total oxidised nitrogen, SRP = soluble reactive phosphorus, DSi = reactive silica

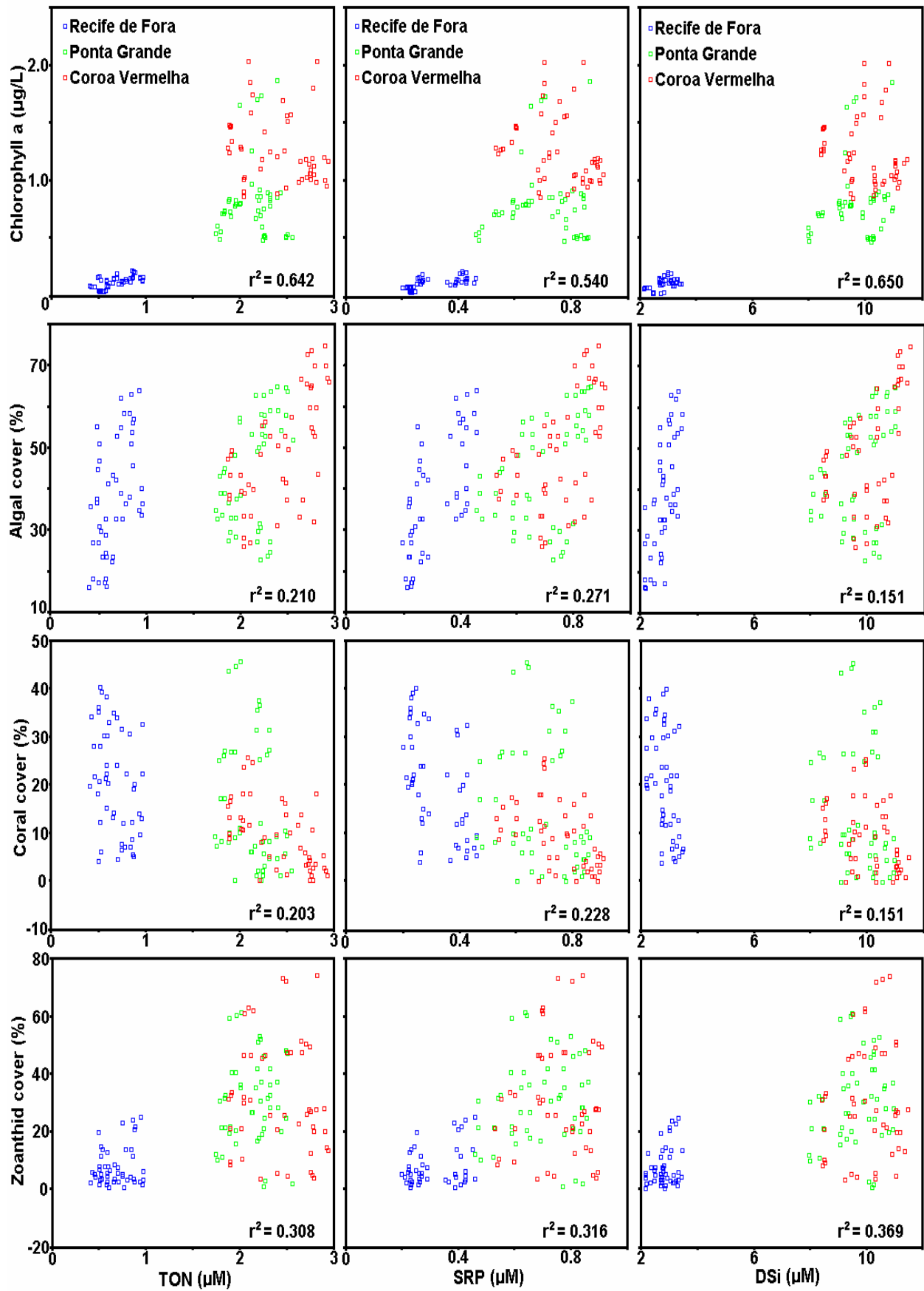


Figure 20.4. Pearson's product-moment correlations between nutrients and chlorophyll *a*, algal, coral and zoanthid cover in the study sites from southern Bahia, Brazil.