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Spatial distribution of light and nutrients in some coral reefs of Costa Rica during January 1997

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Abstract: The proximity of coral reefs to areas of present and future coastal development in Costa Rica highlights the need for assessing environmental conditions important to maintaining healthy corals. In January 1997 a survey of light penetration, inorganic nutrient concentrations, temperature, and salinity was conducted in the patch reefs of Bahía Culebra (Pacific Ocean) and on the Caribbean coast in the fringing reef at Parque Nacional Cahuita and near Limón. Temperature was 28°C at all sites, and salinity ranged from 33 to 36 psu. Light attenuation coefficients ranged from 0.12 to 0.29 m^{-1} in reef areas. Seawater nutrient concentrations were within the range of concentrations reported for tropical reef waters; combined NO_3^- and NO_2^- and PO_4^{3-} were each below 1 µM. NH_4^+ ranged from 0.2 to 7 µM, representing a significant source of nitrogen. The ratio of total dissolved inorganic nitrogen to phosphate averaged 27 for all reef waters. The high nitrate (3.6 µM) and light attenuation (0.95 m^{-1}) values from the surface waters of the La Estrella plume (Caribbean coast) show that this river represents a significant source of nitrogen and light attenuation for the neighboring reefs at Cahuita. This survey provides a useful baseline for future studies, which should monitor these important coastal coral reef areas during both wet and dry seasons.

Key words: Coral reefs, seawater nutrients, light profiles, Cahuita, Limón, Bahía Culebra, Costa Rica.

The coastal waters of Costa Rica include coral reefs in both the Pacific Ocean and Caribbean Sea (Cortés 1993). Although the major Caribbean coral reefs at Cahuita are protected in a national park, several reef sites on the Pacific coast are near beaches slated for major tourism expansion and hotel development (Jiménez 1997). Because the water quality of these reefs may change in response to extensive coastal development, parameters likely to affect reef health should be monitored on a regular basis. The most important water conditions (besides temperature and salinity) that promote vigorous coral reef growth are high water clarity and low dissolved inorganic nutrients.

Water clarity is particularly important for tropical corals, which rely on energetic contributions from their symbiotic dinoflagellate microalgae (zooxanthellae) for growth and calcification (Muller-Parker and D'Elia 1997). Corals are highly susceptible to changes in environmental conditions that result in less available light, such as increased sedimentation from land run-off and eutrophication of the water column. Increased sedimentation and runoff are two of the most pronounced early effects of coastal development. In high precipitation areas especially, clear-cutting of forests and development of agrarian economies result in increased levels of water borne sediment and nutrients, and de-

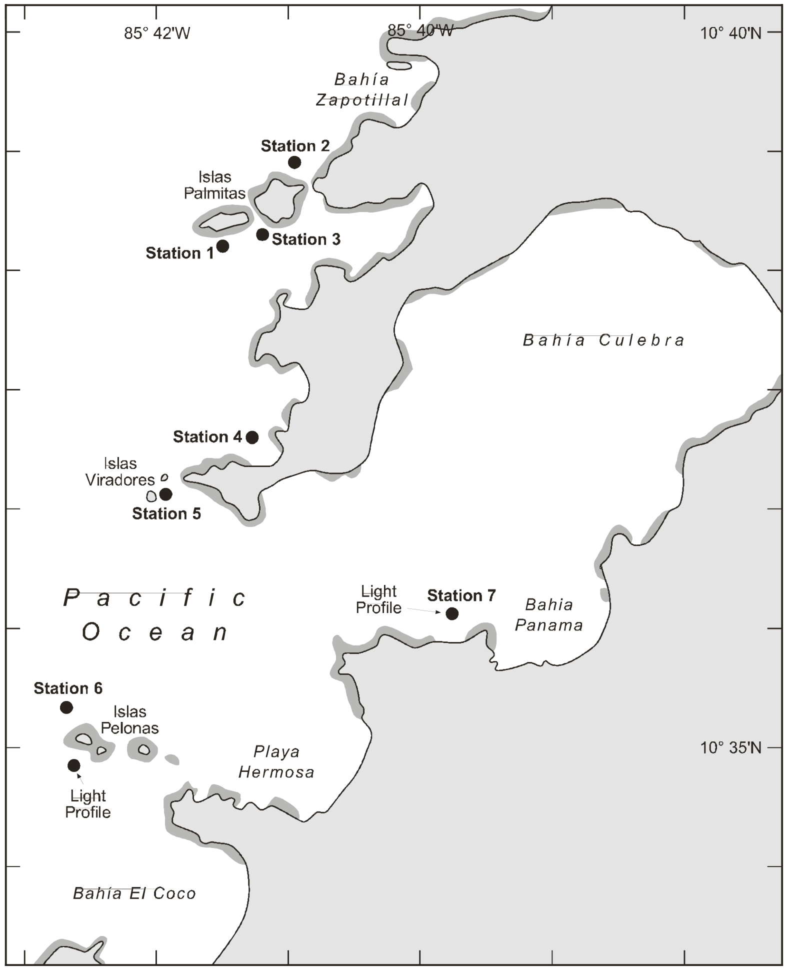

Fig. 1. Location of Stations 1-7 (Bahía Culebra, Guanacaste). The locations of the two spectral light profiles are also indicated.

creases (or increases in the seasonal variation) in salinity. These activities have been associated with a reduction in coral cover and diversity at Cahuita (Cortés and Risk 1985), the largest reef on the Caribbean coast of Costa Rica (Cortés and Guzmán 1985).

Corals thrive in seawater where the supply of the major growth-limiting nutrients, nitrogen and phosphorus, is very low (D'Elia 1988). Nutrient levels around reefs may become periodically elevated due to leached nutrients in land run-off following heavy precipitation, point source inputs (from sewage and industrial effluents), or periodic upwelling of deep, nutrient-rich water. Non-point sources include nutrient inputs from agricultural practices, eroded soils as a result of forest removal, and recreational uses. When chronic, high level nutrient enrichments occur, symbiotic corals have problems regulating their algal populations (Hoegh-Guldberg and Smith 1989, Muscatine *et al.* 1989, Muller-Parker *et al.* 1994) and are prone to physiological stresses that reduce growth and calcification. This situation is exacerbated by nutrient stimulation of growth of other primary producers in the coral reef ecosystem: increased phytoplankton abundance in the water causes a reduction in light, and increased seaweed growth in the absence of increased herbivory can smother and overgrow the corals.

This field study at three sites along the Pacific and Caribbean coasts of Costa Rica was

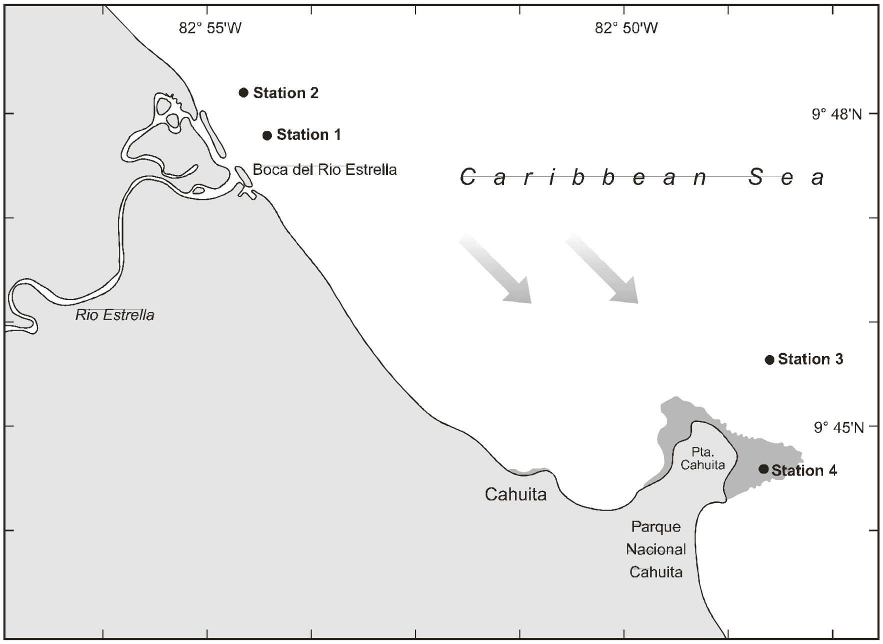

Fig. 2. Location of Stations 1-4 (Cahuita, Limón). The gray arrows show the direction of the prevailing South East coastal current.

conducted during January 1997 to provide an informational survey of water quality parameters for representative coral reefs in Costa Rica. Our study examines light penetration and spectral quality of the downwelling light, temperature, salinity, and inorganic nutrient concentrations of two important coral reef regions of Costa Rica, the patch reefs of Bahía Culebra, Guanacaste Province (Pacific Ocean) and the fringing reefs at Parque Nacional Cahuita and nearby Limón (Caribbean Sea). Bahía Culebra is the most extensive coral reef area on the northern Pacific coast of Costa Rica. Coral diversity is relatively high (16 coral species) and there is a unique *Leptoseris papyracea* reef (Jiménez 1998). The entire area was affected by the 1997/98 El Niño, causing a 5 to 90% reduction in coral cover (Jiménez *et al*. 2001). The coral reef at Parque Nacional Cahuita is the largest (> 5 km^2) and most diverse (e.g. 36 coral species and 24 octocorals) (Cortés 1996-1997) reef in Costa Rica. This reef is impacted by terrigenous sediments which have reduced live coral coverage (40% in late 1970-early 1980 down to 10% in mid 1990) (Cortés and Risk 1985, Cortés 1994).

MATERIALS AND METHODS

A small boat was used to sample water in Bahía Culebra (Fig. 1) and at two Caribbean locations (Cahuita and Limón) on the Caribbean coast (Figs. 2 and 3). Each station was sampled once during a one week period in January 1997. The stations were selected on the basis of their importance as coral habitat and for their proximity to coastal run-off. The Pacific stations were sampled during a tidal period ranging from low tide to the start of the flood tide. The weather conditions were sunny (with partial cloud cover) and no precipitation.

Latitude and longitude at each station was measured with a hand-held Garmin 45 GPS (Global Positioning System) unit. Vertical profiles of water temperature and salinity at 1-m depth intervals were measured with a YSI temperature-salinity meter, and surface values were checked with a thermometer and refractometer. Irradiance (photosynthetically active radiation, PAR) was measured as photon flux density ($\mu mol\ m^{-2}\ s^{-1}$) using two LiCor® quantum sensors: a cosine quantum sensor for irradiance at the surface, and a 4π quantum sensor for un-

Fig. 3. Location of Stations 1-3 (Limón).

derwater irradiance measured at 1-m depth intervals. A series of underwater light spectra profiles were taken at several stations using a LiCor®1800UW scanning spectroradiometer. Light attenuation coefficients (k_d) were calculated for PAR (light quantity) and for different wavelengths of light (light quality). For the latter, the spectral depth profiles were used to calculate linear regressions (slope = k) of the natural log of the underwater irradiance readings for each 50 nm wavelength interval versus depth.

Seawater samples for determination of dissolved inorganic nutrients were collected from the surface and near the bottom (up to 25 m) at each station. Surface water samples were col lected by filling acid-washed and prerinsed bottles with surface water. A Van Dorn bottle was used to collect near bottom (0.25 m from bottom) water samples. Each water sample was filtered on site using a glass fiber filter (GF/F; nominal pore size of 0.7 µm) held in an acid-washed syringe filter holder. Filtered samples were stored in acid-washed polyethylene bottles and kept on ice until they could be frozen. Frozen waters samples were transported to U.S. and dissolved inorganic nutrients (NO_3^-, NO_2^-, NH_4^+ and PO_4^{3-}) were measured using standard oceanographic procedures (Parsons *et al.* 1984) on autoanalyzers at the Chesapeake Biological Laboratory, University of Maryland. Nutrient concentrations are within the detection limits for the colorimetric methods.

RESULTS

Light attenuation and spectral quality: Table 1 lists the geographic coordinates, station names, and PAR light attenuation coefficients (k_d). The clearest water (k_d 0.12 m^{-1}) was located at Isla Uvita (Caribbean) and Güiri-güiri (Pacific). Most of the Bahía Culebra stations had high water clarity. The light attenuation coefficients were uniformly low (<0.18 m^{-1}) at the first six stations; the greatest light attenuation was obtained at Esmeralda, with a k_d of 0.234 m^{-1} for PAR (Table 1). This value is in the range of light attenuation coefficients obtained for the Limón area and for the shallow fringing reef lagoon at Cahuita. Station 1, located in the plume of La Estrella river, has an attenuation coefficient (0.953 m^{-1}) almost 7 times greater than that of Station 3 at Punta Cahuita (Fig. 2). The influence of the river on light penetration is also evident at Station 2, which has the second highest light attenuation coefficient (Table 1).

The spectral distribution of the downwelling irradiance as a function of depth is shown in Fig. 4 for two stations on the Pacific and for

Punta Cahuita (Caribbean). The peak wave- densities of 3 and 62 µmol m^{-2} s^{-1}, respectively.

TABLE 1

Sample stations, dates and times sampled, and water column characteristics

Station	Coordinates	1997 Date, Time (h)	Temp. (°C)	Salinity psu	Light (PAR) attenuation coeff. k_d (m^{-1})
Pacific Coast					
1. Palmitas 1	10° 38.345' N; 85° 41.653' W	Jan 11, 0900	28	33	0.179
2. Palmitas 2	10° 38.737' N; 85° 41.216' W	Jan 11, 0945	28	33	0.153
3. Channel	10° 38.277' N; 85° 41.433' W	Jan 11, 1100	28	34	0.162
4. Güiri-güiri	10° 36.837' N; 85° 41.416' W	Jan 11, 1130	28	34	0.124
5. Virador	10° 36.522' N; 85° 42.097' W	Jan 11, 1215	28	34	0.160
6. Bajo Sorpresa	10° 34.887' N; 85° 42.773' W	Jan 11, 1300	28	34	0.171
7. Esmeralda	10° 35.689' N; 85° 40.157' W	Jan 11, 1340	28	34	0.234
Caribbean Coast					
Cahuita Area					
1. Río La Estrella plume (C1)	9° 48.070' N; 82° 53.685' W	Jan 17, 0930	28	27 (surface) 36 (5m)	0.953
2. Río La Estrella (C2)	9° 48.386' N; 82° 53.879' W	Jan 17, 1045	28	35	0.400
3. Punta Cahuita (C3)	9° 46.310' N; 82° 48.575' W	Jan 17, 1200	28	36	0.144
4. Cahuita Lagoon (C4)	9° 44.307' N; 82° 48.443' W	Jan 17, 1400	-	36	0.288
Limón Area					
1. Isla Uvita	9° 59.473' N; 83° 00.970' W	Jan 18, 1200	28	34	0.121
2. Punta Basurero	10° 00.741' N; 83° 02.825' W	Jan 18, 1330	-	34	0.275
3. Isla Pájara	10° 01.010' N; 83° 04.588' W	Jan 18, 1400	-	34	0.220

See Fig. 1-3 for station locations. Temperature and salinity were constant with depth except where indicated.

lengths indicate the spectral quality of the photosynthetically available light at different depths. For example, at 9 m depth, irradiance at the two Pacific stations is mostly green (peak irradiance at Islas Pelonas is 538 nm and at Esmeralda is 564 nm), with a total photon flux density of 334 µmol m^{-2} s^{-1} and 125 µmol m^{-2} s^{-1} at each station, respectively. At Punta Cahuita, the peak irradiance at 9 m is shifted to blue (496 nm) and the total photon flux density at this depth was 228 µmol m^{-2} s^{-1}. For stations where the particulate load is high due to riverine input (Stations 1 and 2 near La Estrella, Caribbean; Fig. 2), irradiance of all wavelengths is greatly reduced and peaks are shifted towards yellow (Fig. 5a and 5b). At Stations 1 and 2 at 5 m depth, peak irradiances are 556 nm and 554 nm with total photon flux

Since differences in solar conditions at the surface affect underwater irradiances, PAR at each depth was also plotted as a percent of surface PAR. Fig. 5c shows the dramatic reduction in percent light penetration in the river plume (C1) in comparison to the three other Cahuita stations.

Fig. 6 compares the wavelength-specific light attenuation coefficients with depth. These spectral 'signatures' show that Islas Pelonas (IP) and Punta Cahuita (C3) are fairly similar water types, with the least attenuation of ultraviolet and blue light. In contrast, the La Estrella river plume strongly absorbed ultraviolet and blue light, and yellow penetrated the best.

Salinity, Temperature, and Inorganic Nutrients: Table 1 reports the average temperature and salinity for the water column at each station since these parameters did not vary with depth (data not shown), except for salinity in the plume of La Estrella (27 psu at the surface and 36 psu at 5 m; Table 1). Temperature was remarkably

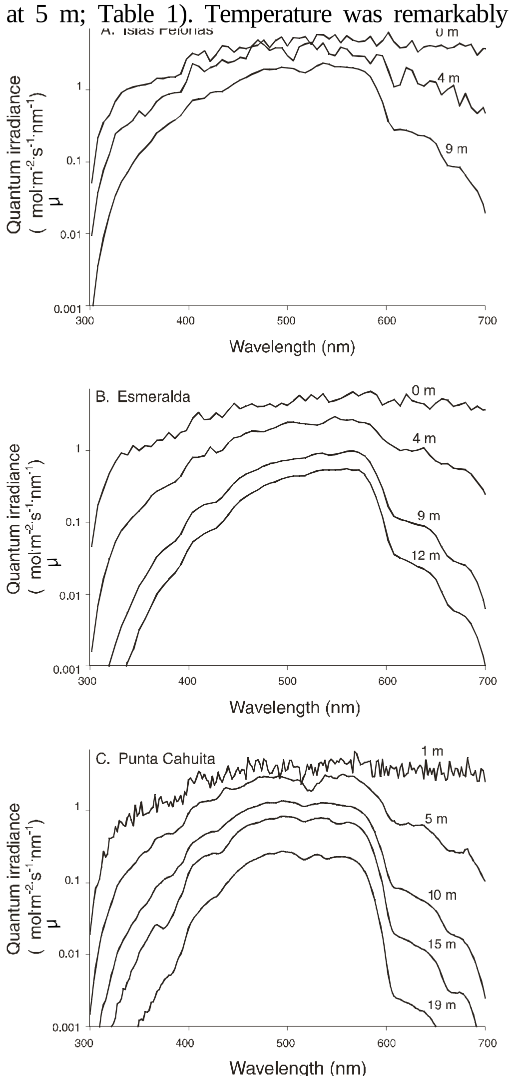

Fig. 4. Wavelength-specific quantum irradiance at selected depths obtained from spectroradiometer scans at three stations: A) Islas Pelonas and B) Esmeralda from the Pacific coast (see Fig. 1 for locations), and C) Punta Cahuita in the Caribbean (see Fig. 2, Station 3). The depths are indicated above each scan.

constant (28ºC) at all coastal sites, which were sampled within a one week period. Salinity ranged from 33-36 and did not vary with depth, except for Station 1, in the plume of the La Estrella river (Table 1).

There are no consistent trends in the distribution of nutrients among the Pacific stations (Fig. 7), although deep water samples had higher concentrations. This trend is especially

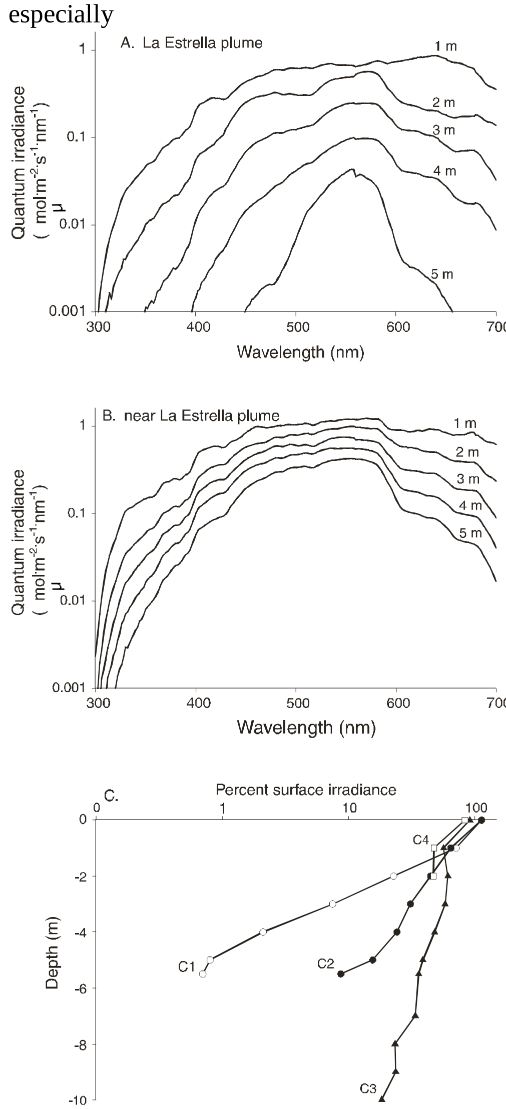

Fig. 5. A and B: Wavelength-specific quantum irradiance at selected depths obtained from spectroradiometer scans at Station 1 (Fig. 5a) and Station 2 (Fig. 5b) near Cahuita. The depths are indicated above each scan. C) Percent light penetration of PAR with depth at the four Cahuita stations (see Fig. 2 for station locations).

evident with respect to total dissolved inorganic nitrogen (DIN = $NH_4^+ + NO_2^- + NO_3^-$), with the exception of Station 1 (Fig. 7). The atomic ratio of dissolved inorganic nitrogen to dissolved phosphate (DIN:DIP) compares the relative availability of nitrogen and phosphorus for primary producers. Ratios below 16:1 (the Redfield ratio) indicate the potential for nitrogen limitation and ratios above 16:1 indicate the potential for phosphorus limitation. The DIN:DIP of seawater surface samples indicated the potential for phosphate limitation at Station 1, and for nitrogen limitation at Stations 6 and 7 (Fig. 7).

The seven Caribbean stations showed much greater variation in nutrient concentrations than the Pacific stations. In the Caribbean, the highest nitrate and phosphate concentrations were obtained at the surface at Station 1 of the Cahuita area stations, in the plume of La Estrella (Station 1, Fig. 8). Conversely, ammonium concentrations were very low in the surface plume. Station 2, north of the plume which flowed in a southerly direction, had low nitrate and phosphate concentrations and a higher ammonium concentration than the surface water at Station 1. For the Cahuita stations, surface nutrient concentrations were lowest at Punta Cahuita (Station 3) and generally low in surface waters of the shallow fringing reef lagoon (Station 4). However, the deep water sample (16 m) from Punta Cahuita had very high ammonium and nitrite concentrations, resulting in high total dissolved inorganic nitrogen concentrations (Fig. 8). The DIN:DIP ratio of most Cahuita water samples was close to the Redfield ratio of 16 (Fig. 8). Surface water at Station 2 and deep water at Station 3 was depleted in phosphorus with respect to DIN. The bottom water in the fringing reef lagoon, with the lowest DIN:DIP of 8, indicated that nitrogen was depleted with respect to phosphorus availability. This water sample did have a relatively high phosphate concentration (Fig. 8).

The nutrient concentrations of seawater samples from the Limón area of the Caribbean were lowest at Station 1 and higher at Stations 2 and 3 (Fig. 8). Ammonium in the surface water at Limón Station 3 was extremely high, resulting in both high total dissolved inorganic nitrogen and high DIN:DIP (Fig. 8). All Limón water

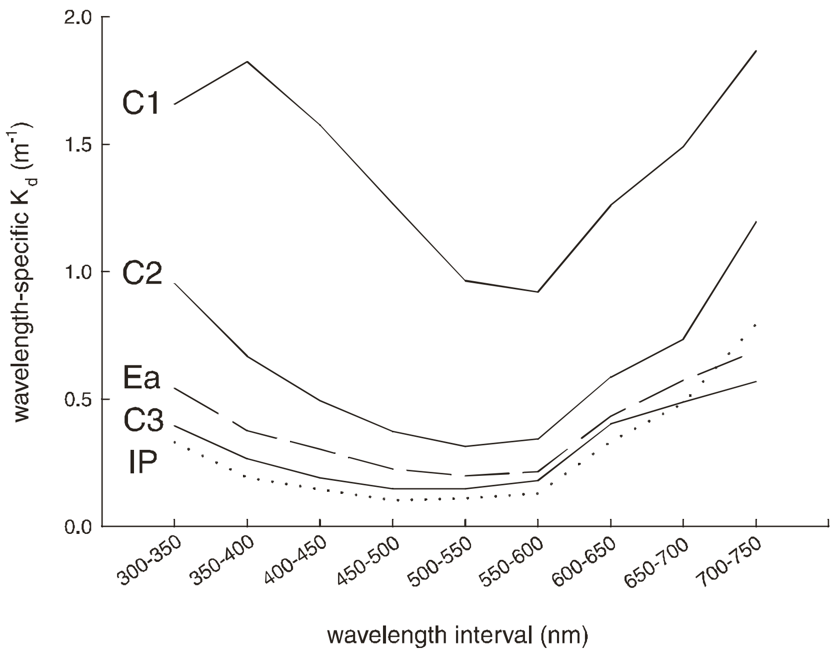

Fig. 6. Wavelength-specific light attenuation coefficients at five stations for 50-nm wavelength intervals. Caribbean stations C1, C2, and C3 refer to Stations 1-3 respectively (see Fig. 2); Pacific stations IP and Ea refer to Islas Pelonas and Esmeralda, respectively (see Fig. 1).

samples had DIN:DIP ratios above 16, indicating phosphate was depleted with respect to nitrogen (Fig. 8).

Table 2 includes the mean values for all Pacific and Caribbean water samples taken during January 1997. Nitrate and phosphate concentrations are slightly lower in the Caribbean than in the Pacific samples. Although the mean am-
monium concentration was much higher in the Caribbean, two very high values (> 14 μM; Fig. 8) influenced this result. When these samples are omitted the mean ammonium concentration drops to 1.51 μM, below the Pacific mean value. In both sets of coastal samples, ammonium contributes substantially

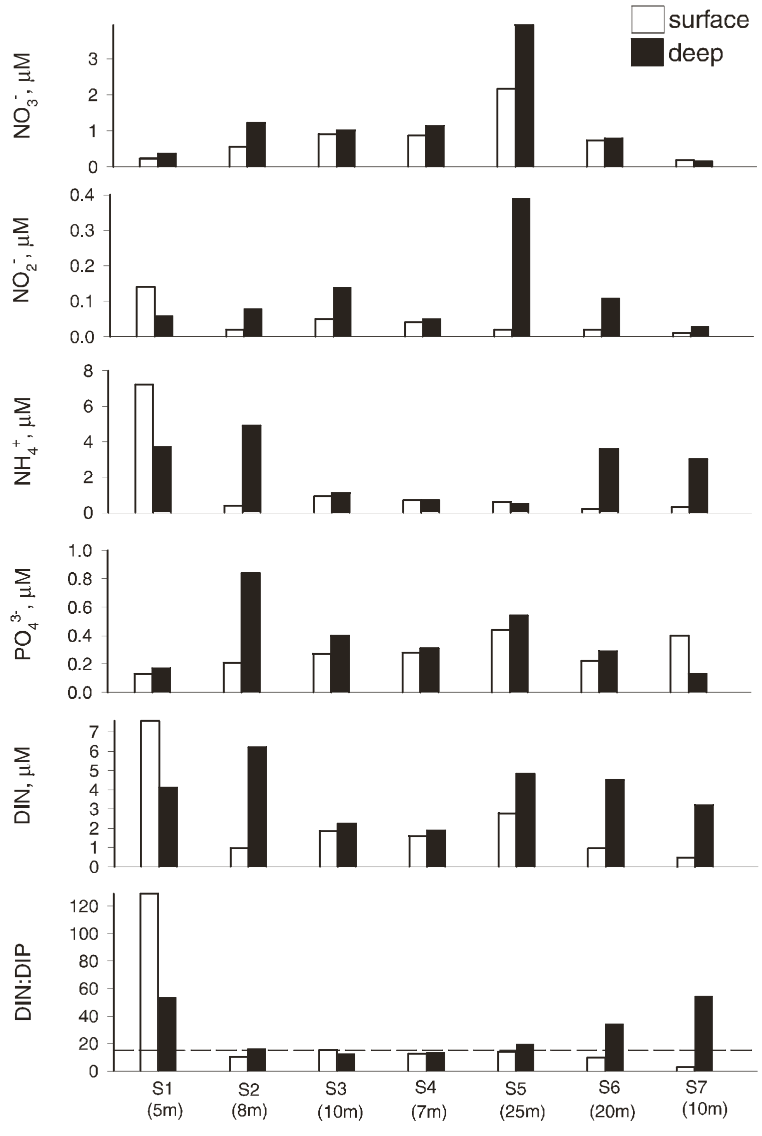

Fig. 7. Inorganic nutrient concentrations ($N0_3^-$, $N0_2^-$, NH_4^+, and $P0_4^{3-}$), total dissolved inorganic nitrogen (DIN), and ratio of DIN to $P0_4^{3-}$ (DIP) of Bahía Culebra stations (Fig. 1); surface water (white bars) and deep water (black bars) concentrations are shown. Collection depths for the deep samples are indicated in parentheses on the bottom horizontal axis. The dashed line in the bottom panel represents the Redfield ratio of 16.

to the total dissolved inorganic nitrogen pool while nitrite represents a small fraction of this pool (Table 2).

The DIN:DIP of the Pacific samples averaged 27 (Table 2). The mean value for the Caribbean water samples is 91, although excluding the two high ammonium values (Fig. 8) results in a mean DIN:DIP of 27. All values are above the Redfield number of 16, indicating a slight potential for phosphorus limitation in these waters.

DISCUSSION

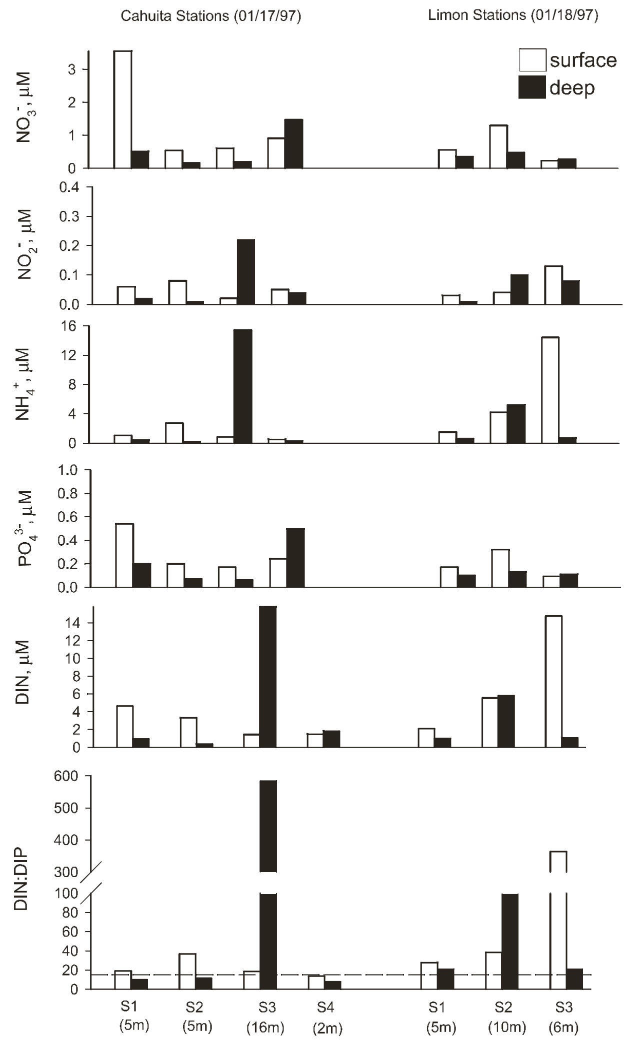

Fig. 8. Inorganic nutrient concentrations ($N0_3^-$, $N0_2^-$, NH_4^+, and $P0_4^{3-}$), total dissolved inorganic nitrogen (DIN), and ratio of DIN to $P0_4^{3-}$ (DIP) of Caribbean samples (Figs. 2 and 3); surface water (white bars) and deep water (black bars) concentrations are shown. Collection depths for the deep samples are indicated in parentheses on the bottom horizontal axis. The dashed line in the bottom panel represents the Redfield ratio of 16.

TABLE 2

Mean seawater inorganic nutrient concentrations of all Pacific Stations (n=19 samples) and all Caribbean Stations (n=14 samples) during January 1997

Inorganic nutrient (µM)	Pacific Coast			Caribbean Coast		
	Mean (s.d.)	Min.	Max.	Mean (s.d.)	Min.	Max.
Nitrate	0.91 (0.87)	0.16	3.94	0.80 (0.89)	0.20	3.56
Nitrite	0.08 (0.09)	0.01	0.39	0.06 (0.06)	0.01	0.13
Ammonium	1.93 (1.96)	0.2	7.2	3.42 (5.10)	0.3	15.4
Total DIN[1]	2.92 (1.98)	0.49	4.83	4.28 (4.98)	0.37	15.82
Phosphate	0.30 (0.17)	0.13	0.84	0.21 (0.15)	0.06	0.54
DIN:DIP[2]	27.28 (28.6)	2.7	128.9	90.81 (169.3)	8.0	583.8

[1]dissolved inorganic nitrogen [2]atomic ratio of total dissolved inorganic nitrogen to phosphate

This descriptive survey of water quality parameters in the Pacific and Caribbean coastal coral reef areas of Costa Rica is useful as a baseline for future studies, which are needed to show how these parameters vary on both temporal and spatial scales. More frequent sampling over longer time scales at these sites is needed to assess how seasonal climate patterns and anthropogenic influences affect water clarity and the concentration of dissolved inorganic nutrients.

Our results indicate that water quality conditions during the sampling period are better for the Pacific corals than for the corals at Cahuita. However, this region is subject to seasonal upwelling (McCreary *et al.* 1989), which is likely to decrease light penetration and increase the supply of nutrients, as shown for the Pacific coast of Panama by D'Croz and Robertson (1997). In view of the anticipated rise in coastal development and hotels in the area, which will contribute to land run-off and point sources of nutrients, corals in Guanacaste may also be at risk. Frequent monitoring of water quality parameters during coastal development during both dry and wet seasons is recommended for detection of potentially stressful trends in reduced light penetration and increased nutrients in waters containing patch reefs.

For the Caribbean, we show that the river La Estrella strongly influences the quantity and quality of photosynthetically-active radiation penetrating coastal waters near the national park at Cahuita (Table 1, Fig. 5). The river is also a significant source of nitrate and phosphate (Fig. 8). Depending on the direction and volume of coastal flows, the river could affect light penetration and nutrient supply for corals at Cahuita. Just offshore at Punta Cahuita, clear water and low surface nutrients prevail. Hydrographic studies are clearly needed to assess the relative contribution of these two sources of seawater to the reef during the dry and wet seasons under a range of coastal conditions. In January 1997, the corals at Cahuita experienced moderate light attenuation (Table 2) and moderate nutrients (Fig. 8). It is likely that these corals experience stress occasionally or on a regular basis from a reduction in light penetration and elevated nutrient loads. During the January 18 survey, the Caribbean stations near Limón showed fairly good water quality in terms of light penetration and low nutrients.

Light attenuation and spectral quality: Te (1997) argued that the light attenuation coefficient (k_d) for photosynthetically active radiation is an ecologically meaningful unit for coral reef studies, since it can be used to model production by corals if the relationship between photosynthesis and irradiance is known. Although we do not know the photoadaptive abilities of the corals in the patch and fringing reefs of Costa Rica, comparison of the k_d values show that most sites had fairly low coefficients in January 1997 (Table 1), well below the range of values compiled by Kirk (1994) for coastal waters world-wide but higher than for most oceanic waters. It is likely that light penetration during January was sufficient to sustain photosynthesis by zooxanthellae in the corals; seasonal comparisons of light penetration at these sites are needed to determine how light penetration varies annually. In contrast, light penetration in the plume of La Estrella was similar to that of highly eutrophic estuaries like the Delaware and Chesapeake Bays in the U.S. (Kirk 1994), and is likely to be even further reduced during periods of high flow. The river could drastically reduce the amount of light available to corals at Cahuita, especially when high flow periods are accompanied by strong coastal swells which resuspend shallow sediments.

The spectral quality of light as a function of depth depends on the concentration of dissolved organic materials and sediments in seawater (Kirk 1994). Substantial alteration of the underwater light field occurred in the plume of La Estrella, with essentially no ultraviolet, blue, and red light available to primary producers at 5 m depth (Fig. 5a). The spectral quality of light between the two Pacific sites, Islas Pelonas and Esmeralda (Fig. 4a and 4b), was also quite different. Far more ultraviolet and blue light penetrated at Islas Pelonas (see also Fig. 6), which is more isolated from coastal run-off influences (Fig. 1). Esmeralda is a more coastal water type, with a greater proportion of green light and very little ultraviolet light at depth (see also Fig. 6). "Sun corals" adapted to high light and ultraviolet (e.g. *Pocillopora damicornis*) live at Islas Pelonas while more “shade corals” (e.g. *Leptoseris papyracea*) that cannot tolerate UV exposure are found at Esmeralda (pers. obs.). It was not possible to obtain an adequate spectral profile in the fringing reef at Cahuita because of the shallow depth (2 m), light reflection from the bottom, and wave refraction at the surface (data not shown). The spectral quality of the light on the fringing reef will be influenced by the relative contributions of water from Punta Cahuita (Fig. 4c) and from the plume of La Estrella (Fig. 5a). However, greater light penetration is accompanied by greater exposure to UV light (Fig. 4c), which could be damaging to the shallow corals at Cahuita.

There are few comparable studies of light penetration at different tropical coastal sites. Dustan (1982) compared the underwater light field in the fringing reefs of Jamaica on a sunny day and under storm conditions. He found that storm conditions decreased total irradiance and shifted maximum transmission towards longer wavelengths, as shown for more turbid sites in this study (Figs. 4-6). If corals can absorb light effectively at different wavelengths by changing their pigment complement, subtle changes in light quality may be unimportant. However, differences in ultraviolet light penetration and total irradiance are known to be important determinants of the photoecology of corals and other reef organisms (Shick *et al*. 1996). With continued stratospheric ozone depletion, increased penetration of ultraviolet light at sites such as Islas Pelonas could have important ecological consequences to the coral reef community (Lesser 2000).

Inorganic Nutrient concentrations: A thorough survey of coastal oceanographic conditions was conducted for the Pacific and Caribbean coasts of Panama by D’Croz and Robertson (1997) with weekly samples taken over a three year period. These authors found pronounced differences in nutrient concentrations during the wet and dry seasons on both coasts, as well as with the occurrence of seasonal upwelling events. Their dry season coastal nutrient concentrations are comparable with our surface water results for the non-riverine stations (Figs. 7 and 8). In general, the seawater nitrate and phosphate concentrations (Table 2) fall within the range of concentrations reported for tropical reef waters (<1 µM nitrate and <0.5 µM phosphate; D’Elia 1988). The high surface nitrate concentration (3.6 µM) of the La Estrella plume indicates that this river could supply significant amounts of nitrogen to the fringing reefs at Cahuita. With respect to total dissolved inorganic nitrogen, the mean value of 4.28 µM, with a range from 0.4 to 16, on the Caribbean coast (Table 2), is higher than reported by D’Elia and Wiebe (1990) for a variety of reef sites world-wide.

Our survey is limited since we can only compare the distribution of inorganic nutrients in single water samples obtained from the three sites during a single week in January 1997. In order to better understand the temporal and spatial availability of nutrients to corals and other reef organisms, and to detect the influence of seasonal upwelling events on the Pacific coast, frequent sampling over longer periods of time are required. Current monitoring programs conducted by CIMAR, University of Costa Rica, along both coasts will provide valuable information in this regard.

Ecological importance of study sites: The Pacific and Caribbean coastal regions differ with respect to rainfall, vegetation, and land use practices, as well as in coral species and reef structure (Cortés 1986, 1993). The two reef areas we examined in this study (Bahía Culebra and Cahuita) are among the most important in the country in terms of size, diversity and economic value. At the same time, both areas are impacted by human activities. The human impact on the Pacific coast is recent and results from tourist developments in the watershed (Jiménez 1997). There has been a long-term impact of terrigenous sediment input to the reef on the Caribbean coast (Cortés and Risk 1985). At Cahuita a continuous decline in reef cover was observed between the late 1970s, early 1980s and the mid 1990s (Cortés 1994). Increased sedimentation has been observed in Bahía Culebra (Jiménez *et al.* 2001). A decrease in light penetration due to sediments or increased nutrient loading (plankton increase) could result in coral reef degradation, as well as direct sediment effects on the corals and growth of macroalgae from enhanced nutrients.

It is important to monitor these reef areas to determine if water quality is declining. Basic water quality monitoring is presently conducted in both areas. In Cahuita the CARICOMP protocol is used (Cortés 1998). Climatic, oceanographic and biological monitoring is being conducted at Bahía Culebra (Cortés *et al.* unpubl. obs.). The monitoring of these reef areas have shed some light on the natural cycles of each region. This information is critical to furthering our knowledge of reef conditions so that we may make informed decisions about how to protect these important coastal coral reefs. It will also be important to study how the corals in each region respond to changes in water quality parameters, especially with respect to photosynthesis of the zooxanthellae, calcification, growth, and reproduction.

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