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Basic limnology of Lago Bonilla, a Tropical lowland lake

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Abstract: Lago Bonilla, located 370 m above sea level on the Eastern slopes of Volcan Turrialba, Costa Rica, was visited four times during 1990-1991. Basic limonological data were recorded in each visit. It is oligomictic, mixing during the coldest and windiest months sometime between Nov. and Feb, and eutrophic, with low Secchi transparencies, Cyanobacteria dominance and almost permanent anoxic conditions in the deepest portion. A shift in N to P ratio was observed, indicating a variation in the limiting factor during the year; N becomes limiting during the driest months probably as a result of a lower input from the catchment due to lower runoff, coupled with a higher P input from the sediments during deep mixing periods. However, limitation by P was probably stronger than N when it occurred, according to the N/P ratios. Phytoplankton in epilimnetic waters comprised 58 algal species, and was dominated by Cyanobacteria and Chlorophyta. Only a few species dominated the community, mainly *Cylindrospermum minimum.* and *Tetraedron minimum*, rendering low diversity values. Zooplankton was also poor: only seven species were found. There were some indications of vertical migrations of some zooplankters.

Key words: Lakes, limnology, tropics, plankton, Costa Rica.

Lago Bonilla is located 370 m above sea level, on the slope of Volcan Turrialba, Costa Rica (9° 59'40" N and 83° 36'14" W), in a region with a very humid and hot weather, with no water deficit in the soil at any time of the year (Herrera 1986). The hills around the lake are low, with gentle slopes, covered with pastures and remnant rainforest.

The work done so far in other Costa Rican lakes, and other tropical lakes of the World, have shown that tropical lakes at low altitudes are usually thermally stratified with one or a few deep mixing periods in a year (Hutchinson & Löffler 1956, Beadle 1974). In Costa Rica, as has been discussed for Arenal Reservoir, there is an expected mixing period from December to Feb. due to the lower temperatures and stronger winds at this time of the year (Umaña & Collado 1990). Based on the location of Lago Bonilla and the low topography of its surroundings, one may expect the lake to be monomictic or oligomictic.

There has been some prior work in the lake. Mora (1989) described its morphology and gave a bathymetric map, from which the morphometric parameters were calculated (Table 1). She found that the lake was not stratified in Feb. 1989, although a week later the lake developed an incipient stratification of oxygen and temperature. She described the lake water as soft (ca. 18 mg/l of Calcium plus Magnesium), dilute (Conductivity between 75 and 80 mmhos/cm), with a slightly alkaline pH (7.18-7.41). Bumby (1982) described the littoral vegetation, which comprised ten species. She also described the water of the lake as soft bicarbonate waters, with HCO_3^- dominating over sulphate and chloride. In her paper she reported the deforestation of the lake's watershed, and cattle grazing on its border, which have resulted in eutrophication of the lake, with low Secchi transparencies. Horn & Haberyan (1993) sampled Lago Bonilla in July 1991. The lake showed oxygen stratification but very little difference in temperature or water chemistry between deep and surface water, leading the authors to suggest that the lake probably turns over yearly. Northrop and Horn (1996) recov-

TABLE 1

Morphometric parameters of Lago Bonilla.

Area (A)	29.5 Hm^2
Volume (V)	3.0 Hm^3
Max. Depth (z_m)	30.0 m
Mean Depth ($\bar{z}$)	10.2 m
Shore Line (L)	2239.5 m
Shore Line Development (D_L)	1.16
Volume Development (D_V)	1.02
Relative Depth (z_r)	4.90
Length (l)	908.2 m
Mean Breadth (b)	324.8 m
Max. Breadth (b_m)	406.6 m

ered sediment cores from Lago Bonilla and adjacent Lago Bonillita for paleoecological analyses. They were unable to determine the ages of sediment cores from Bonilla, owing to problems with radiocarbon dating, but their 9.7 m sediment core from Lago Bonillita was shown to span approximately 2500 years. In cores from both lakes they found pollen grains and charcoal fragments indicative of prehistoric agriculture and forest disturbance in the area.

The present paper presents the results of four visits to the lake over the period of a year (Aug. 1990 to Jun. 1991), with the aim to study its mixing pattern and planktonic assemblages.

MATERIALS AND METHODS

The lake was visited four times in one year to cover both the rainy and dry seasons. Sampling was done in Aug. and Nov. 1990, and Feb. and Jun. 1991 at the deepest part of the lake.

Depth profiles of dissolved oxygen, temperature (YSI meter model 57) and conductivity (YSI meter model 33M S-C-T) were determined as well as the Secchi depth. Subsurface replicated water samples for pH, chlorophyll, nutrients and phytoplankton were collected using a Niskin water sampler. Samples of 100 ml for phytoplankton were also taken and preserved with Lugol's acetic solution. Chlorophyll a determinations were corrected for phaeopigments with the dilute hydrochloric acid method. A volume of 500 ml was filtered and chlorophyll was extracted with 90% acetone (Strickland & Parsons 1968).

Water for nutrient determinations was filtered through glass-fibre filters (Whatman GF/C equivalent) and stored in refrigeration (4°C) for no more than three days before analysis. Samples were analyzed at the CIMAR laboratories. Soluble reactive phosphate (SRP) was measured with the molybdate blue method (Golterman & Clymo 1969). Nitrite was determined by the sulfanilamide-NED method (ibid.). For nitrate the cadmium reduction column method was used. Ammonia was measured with the phenate method (APHA 1980).

Phytoplankton samples were settled in graduated cylinders in the laboratory for a minimum of 48 hours. The excess of water was siphoned out with an "U"-shaped siphon. The remnant volume was centrifuged to further concentrate the sample down to 1 ml before counting. Aliquots of 0.1 ml were used for the counts. Aliquotes were placed in a Palmer-Malloney cell and counted under 40x objective (total power of 400x). Two diametral transects of 25 optical fields each were scanned.

Results were expressed as units per volume, with units being either filaments, colonies, coenobia or individual cells, according to the species morphology. Species were separated by morphotypes to which a numerical code was assigned. Each morphotype was identified to the lowest taxonomic level possible (West & West 1904, 1905, 1908, 1912, 1923, Prescott 1962, Huber-Pestalozii 1968 , Whitford & Schumacher 1973, Komárek 1985). No more than 100 units per species were counted (modified from Lewis 1978). Rare species were counted until the limit of optical fields was reached.

Zooplankton was sampled with vertical (from 20 m deep) and surface horizontal tows, using a 64 mm mesh net. Samples were preserved with 4% formalin. Zooplankton species identifications were made by C. Collado, who has previously published on zooplanton of this and many other lakes in Costa Rica (Collado 1983, Collado *et al.* 1984, Haberyan *et al.* 1995).

RESULTS

Lago Bonilla is a warm water lake, with temperatures from 26.5 to 29°C at the surface, and from 25.1 to 26.5°C at the bottom, with a heat content that fluctuated between 322 cal cm^{-2} and 347 cal cm^{-2} (mean Q= 336 cal cm^{-2}). The water column was found stratified during three visits (Fig. 1a). In Feb. 1991 the surface temperature decreased by 2.5°C, and the stratification was less pronounced, yielding a lower value of the Birgean (1916) work of the wind (Table 2). The dissolved oxygen shows a sharp decrease below 4m of depth, even in Feb.. In Aug. 1990 a peak in oxygen was observed at the surface, with an oversaturation (126-170% saturation) (Fig. 1b). Conductivity showed an increase with depth, specially below 8m (Fig. 1c). In Feb. 1991 the chemocline was lowered down to the deepest waters of the lake and conductivity was relatively homogeneous down to 15 m.

The pH values varied between 6.48 and 8.80, decreasing with depth (Aug. 1990, Fig 2). Nutrient levels varied considerably in the study period (Fig. 3 a,b,c). In general NO_3^- was the most abundant form of N, with levels up to 285 mg $N\text{-}NO_3$/l in Aug. 1990, but decreasing to not detectable levels in Nov. 1990. NH_4^+ was always present in moderate levels (between 7.3 to 68.3 mg N-NH4/l). Soluble reactive phosphate (SRP) was present in small amounts, most of the time below the detection point (max. 7.7 mg $P\text{-}PO_4$/l in Aug 1990). The concentration of SiO_2 measured in Jun.1991 was high (5628.9 mg m^{-3} SiO_2).

All inorganic N fractions were added (DIN) and their proportion relative to SRP (DIN/SRP) was calculated, to get an indication of possible limitation by either of the two nutrients. The ratio DIN/SRP varied among the sampling dates, giving some preliminary indication of a shift in the limiting factor (Fig. 2e), values indicated that P limitation might be stronger when it occurs than N. These results are now being tested with *in situ* bioassays.

A total of 58 species of algae were observed in the phytoplankton in all samples collected. Of these, 27 belonged to the Chlorophyta. The groups that followed were Pyrrhophyta with 9 species and Cyanophyta with 8. Other groups were less diverse (Table 3). With the exception of Aug. 1990, Cyanophyta was the most abundant group, with a abundance greater than 50%. Chlorophyta was the other dominant group, which attained a maximum of 90.8% in Aug. 1990. Dinoflagellates and diatoms were the remaining components of the phytoplankton (Table 3).

TABLE 2

Values of the Work of the Wind according to Birge (1916).

Date	Ws	Wb	WT
Aug. 1990	206.9	445.2	652.1
Nov. 1990	220.3	206.5	426.8
Feb. 1991	67.5	27.6	95.1
Jun. 1991	281.4	195.0	476.4

These values are a measure of the resistance of the water column stratification against mixing by the wind and provide a way of comparing the relative stability of different temperature profiles from a lake. **Ws** gives an estimate of the amount of work necessary to break the stratification and **Wb** gives the amount of work necessary to distribute homogeneously the heat content of the water. **WT** is the sum of both and gives the total amount of work. Units are in Nm/m.

TABLE 3

Number of species per taxonomic group by date. Diversity Values are H': Shannon Diversity Index. J: Equitability based on Shannon's formula (J=H'/Hmax).

Date	Chlor	Pyrrh	Bacil	Cyano	Other	H'	J
13/8/90	11	2	1	6	0	1.44	0.48
	12	3	2	6	3	1.59	0.49
23/11/90	11	5	3	4	3	1.79	0.55
	9	4	3	5	3	1.69	0.53
22/2/91	13	3	1	6	2	1.61	0.50
	7	4	1	5	3	1.58	0.53
13/6/91	10	4	0	4	2	1.88	0.63
	7	3	0	4	3	1.51	0.53

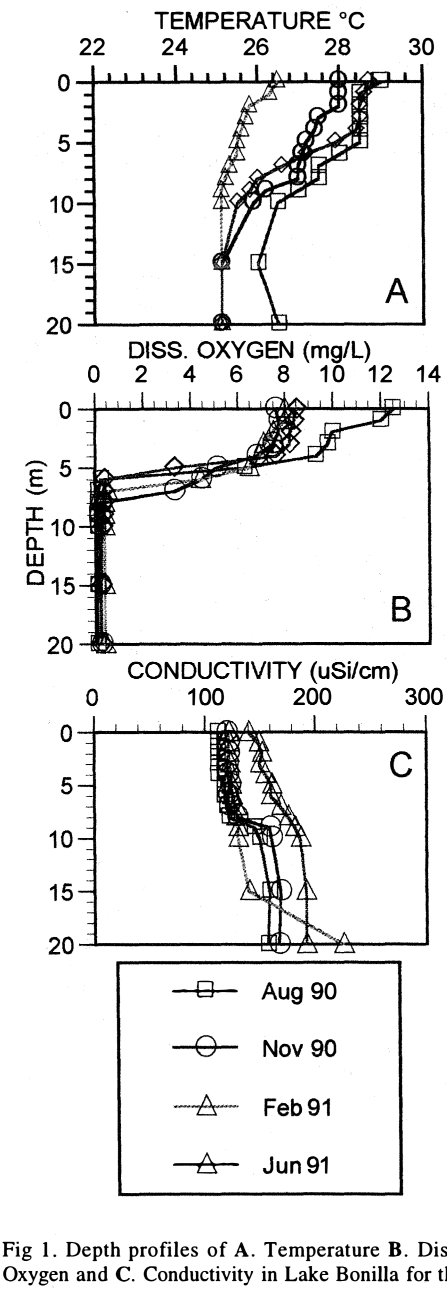

Fig 1. Depth profiles of **A**. Temperature **B**. Dissolved Oxygen and **C**. Conductivity in Lake Bonilla for the four sampling dates (Aug. 1990, Nov. 1990, Feb. 1991 and Jun. 1991).

The number of taxa per sample varied between 16 and 32, being higher for the deep mixing period (Nov. and Feb.). Shannon's index values ranged between 1.29 and 1.88, and equitability values between 0.42 and 0.63 (Table 3). The most important species were: *Cylindrospermum* cf. *minimum*,

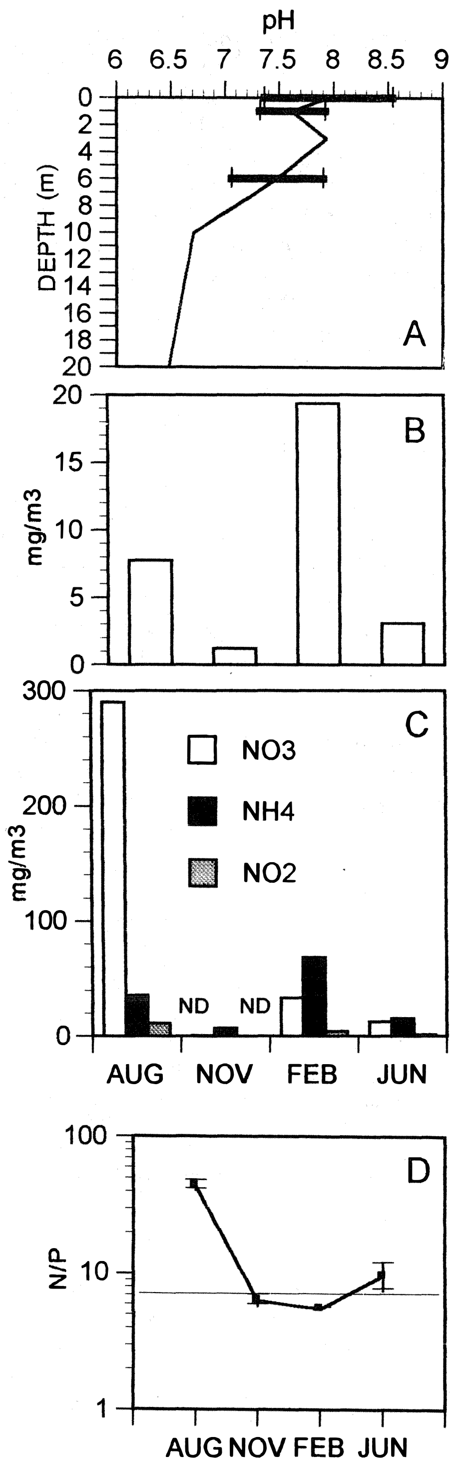

Fig. 2. Summary of pH and nutrients in Lake Bonilla. **A.** Depth Profile of pH. Variation with time of: **B.** Orthophosphate. **C.** Inorganic N (N-NO_3, N-NO_2 and N-NH_4). **D.** N/P ratios.

Dactylococcopsis sp., *Tetraedron regulare, Tetraedron minimum, Coelastrum reticulatum, Anacystis montana* and *Peridinium inconspicuum.* This later species presented low densities but was always present in the counts.

Total density varied between 1589 and 7791 individuals per ml. Density was higher during Nov. 1990 and Feb. 1991 (Fig. 3a). Chlorophyll a concentration showed lower val-

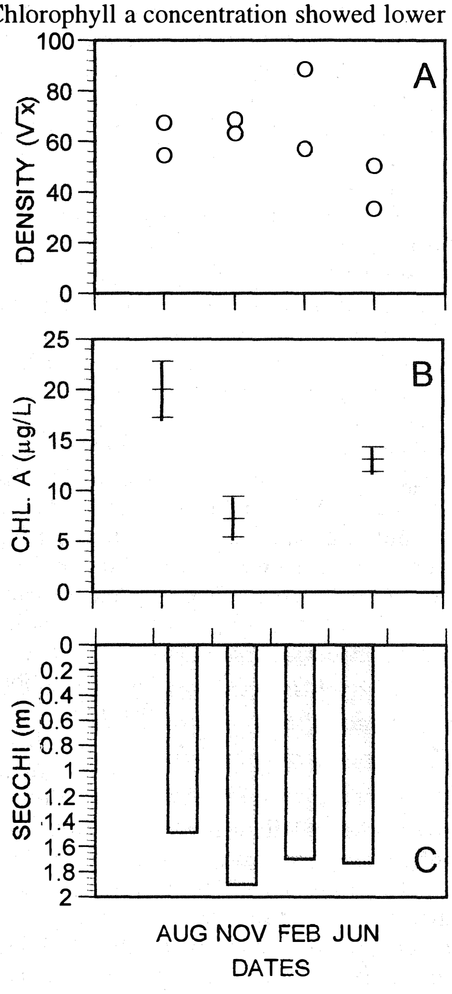

Fig. 3. Values of: **A**. Total density of phytoplankton; **B**. Chlorophyll a from subsurface samples and; **C**. Secchi transparencies; at the four sampling dates in Lake Bonilla.

ues in those months (Fig 3b), with peaks in Aug. 1990 and Jun. 1991. Secchi depth was low, between 1.5 and 1.9m; the greatest values were measured in Nov. 1990 and Feb. 1991 (Fig. 3c). The temporal variation in phytoplankton species composition did not show major shifts in the dominant groups. Basically, a few green and blue-green species dominated throughout the study period, with two species sharing dominance: *Tetraedron minimum* and *Cylindrospermum minimum.* Green algae were dominant in Aug. and Nov. 1990 (Fig. 4a), while

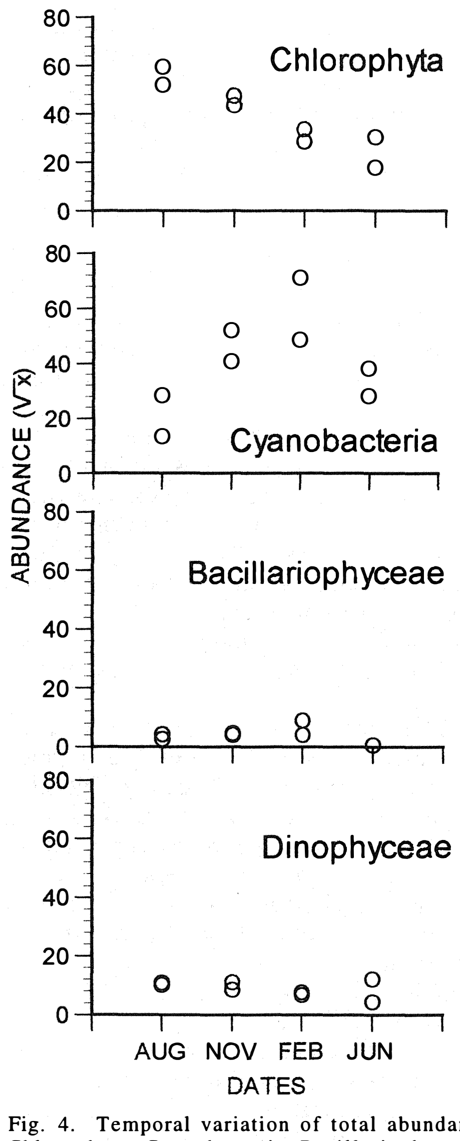

Fig. 4. Temporal variation of total abundance of Chlorophyta, Cyanobacteria, Bacillariophyceae and Dinophyceae in the surface waters of Lago Bonilla from Aug. 1990 to Jun. 1991 (the square root transformation was used in the graphs).

Cyanobacteria dominated in Feb. and Jun. 1991 (Fig. 4b). Diatoms showed a maximum also in Feb., but they didn't become dominant at any time (Fig. 4c), nor did the dinoflagelates, which showed the lower values in Feb. (Fig 4d).

Seven species of zooplankton were identified: 2 Cladocera (*Bosmina hagmanii* and *Ceriodaphnia cornuta* (form without horns)), 2 Copepoda (*Microcyclops* sp, *Mesocyclops thermocyclopoides*) and also nauplii larvae and cyclopoid juveniles, and 3 rotifera (*Keratella* sp., *Polyarthra vulgaris* and *Hexarthra intermedia*). The composition in vertical and horizontal surface samples was different. Both Cladocera and the *Microcyclops* sp. appeared only in the vertical tows, indicating a deeper location of these species within the lake.

DISCUSSION

Lago Bonilla is an oligomictic lake, mixing briefly sometime during the coldest and windiest months from Nov. to Feb. (dry season). The lake stratifies again in early March. A sampling performed in March 1989 showed that the lake was stratified. This result agrees well with the report of Mora (1989), who found the lake mixing in mid Feb. and developing an incipient stratificaton by late Feb.. The low topography of its surroundings and the scarce vegetation allow the wind to blow over the lake. Winds blow in the direction of the main axis of the lake, mixing it completely during the circulation event.

Based on several characteristics of the lake it is possible to classify it as a mildly eutrophic lake. One of these characteristics is the persistent clinograde oxygen profile. Even in the deep mixing period the bottom waters quickly become anoxic again, as a result of large amounts of organic matter being decomposed in the deep portion of the lake. The low Secchi values are also typical of an eutrophic lake, however, it seems to be more related with sediments washed into the lake during the rainy period since transparency was lower in the rainest months sampled. The lower total algal density at these times may also indicate some degree of light limitation by silt. The abundance of filamentous Cyanobacteria, which was observed accumulating just beneath the surface on several occasions is another indication of eutrophic conditions, (but see bellow).

Shifting in the limiting nutrient during the year has been observed in many lakes (Sommer 1989), incluiding tropical lakes (Setaro & Melack 1984). P seemed to become more limiting to algae growth in Aug. than was N at other times of the year. The lack of P relative to N may be a result of cattle raising and agriculture in the catchment area. N in the form of nitrate is known to reach the watercourses more easily via runoff and seepage than phosphate since the latter is easily complexed with aluminum and iron oxides (Parker 1994). Agriculture fertilizers and cattle manure are an important source of inorganic N for rivers and lakes, specially in deforested areas (Payne 1986, Parker 1994).

Low DIN/SRP have been documented for some lowland streams in the Atlantic slope of Costa Rica (Triska *et al.* 1993) associated with active volcanic geothermal systems that contribute soluble reactive phosphate. Values of DIN/SRP as low as 3 indicate a high P availability , so that N is more likely to become limiting, in agreement with some literature reports of N limitation in tropical lakes (e.g. Henry & Tundisi 1983). However, there is no evidence so far to indicate that a similar situation occurs in the Lake Bonilla basin.

A plausible explanation for the observed shift might be as follows. The input of N to the lake may decrease during the dry season due to lower runoff from the catchment area. During the deep mixing event, occurring in the first half of the dry season, P becomes more available since it is brought up from sediments by the mixing of deeper layers (Margalef 1983). The vertical mixing introduces P to the euphotic zone and causes a further lowering of the DIN/SRP ratio. The data support this view, since N was less available than P during drier and deep mixing period (Nov. and Feb.). However, it is possible that N may limit the phytoplankton growth even more strongly during the driest months (March through May), just after the wind driven mixing event.

Phytoplankton species composition in Lago Bonilla agrees well with the reported composition of tropical assemblages. The richness of Chlorophyta, and high abundance of Cyanobacteria, as well as the scarcity of groups such as Chrysophyta and the paucity of diatoms, are well known features of tropical freshwater phytoplankton (Umaña & Collado 1990, Umaña 1985, Payne 1986). In a survey of several lakes in Costa Rica, in July-August 1991, the phytoplankton of lake Bonilla also showed a codominance by chlorophytes and cyanobacteria (Haberyan *et al.* 1995).

Dominance was not high, rather it was shared among a few abundant species. At no time between Aug. 1990 and Jun. 1991 did a single species attain a percentage greater than 50% in epilimnetic waters. Due to this situation seasonal changes in dominance were not evident, and there were no major shifts in species composition during the sampling. However, a tendency was noted for green algae to decrease from Aug. '90 to Feb. '91 and to slightly increase by Jun. '91. On the contrary Cyanobacteria showed an increase from Aug.'90 to Feb.'91, just at the time when DIN/SRP ratios were lower, suggesting a low N availability.

This shared dominance between Cyanobacteria and small sized green algae differs from typical eutrophic conditions as reported in the literature (cf. Margalef 1983, Sommer *et al.* 1986). Although *Cylindrospermum minimum* could fix N (Round 1973) it was not highly dominant even at times of possible N scarcity. The codominance of Cyanobacteria and small greens such as *Tetraedron minimum*, and *T. regulare* is unusual. One possible explanation is that eutrophication in this lake does not come from an unbalanced high input of P, since the lake is far from the influence of any city or town. It rather comes from the input of cattle manure and runoff from a partially deforested watershed used mainly for cattle. This means that inputs of nutrients are relatively richer in N forms such as nitrate than in P. As noted above, P becomes more limiting than does N.

Diversity indices of phytoplankton were low compared to other Costa Rican lakes (Umaña unplubished data), with few species dominating the community. It has been claimed that phytoplankton in tropical lakes is less diverse than in lakes at higher latitudes (Lewis 1978, Payne 1986) as a result of the higher seasonality of temperate regions which drives a predictable succession in phytoplankton composition well described in the literature (e.g. Reynolds 1984, Sommer 1989). No such succession is apparent in this lowland tropical lake, which seems to be always under summer conditions (c.f. Kilham & Kilham 1990). The observed low diversity may also be the consequence of its eutrophic condition (Margalef 1983).

The zooplankton showed a poor species diversity, with only seven species, all of which have small body size. The lack of big zooplankters has been described as typical of many tropical lakes (Fernando 1980). One possible reason for this fact is a strong predation pressure all year round, exerted mainly by vertebrate predators. Fishes are mainly visual predators (Sommer 1989) preying preferrably upon the large bodied Cladocerans and Copepods. This may be the case in Lake Bonilla, where a rich ichthyofauna seems to be present including small characids and poecilids that were observed close to the shore. High temperatures have also been proposed as a reason for small bodied zooplankters in tropical lakes (Fernando 1980). There seems to be a typical vertical migration of the zooplankton since vertical and surface horizontal tows yielded different catch compositions. *Ceriodaphnia cornuta*, *Bosmina hogmanni*, and *Microcyclops* sp. were the species which showed a deeper distribution during the day. Haberyan *et al.* (1995) also report the presence of *Tropocyclops prasinus* in lake Bonilla.

The absence of large, efficient filter-feeding zooplankton coincides well with the dominance of small sized algae as noted before. The small zooplankters feed on bacteria rather than phytoplankton (*Ceriodaphnia*, some rotifers) hunt selectively for special items (*Bosmina*) (cf. DeMott & Kerfoot 1982, Lair 1991, Fulton 1988), or are raptorial feeders, feeding mainly on larger cells or as predators (Cyclopoids) (cf. Gliwicz & Umaña 1994, DeMott & Watson 1991). These factors can also enhance the abundance of small celled algae, which are also expected to have high growth rates, outcompeting the large species.

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RESUMEN

El lago Bonilla se localiza a 370 m sobre el nivel del mar, en la vertiente oriental del Volcan Turrialba, Costa Rica. El lago fue visitado cuatro veces en un año, durante las cuales se colectó la información limnológica básica. El lago es monomíctico tibio, circulando durante los meses más fríos y ventosos del año, de Noviembre a Febrero. Se clasificó eutrófico en base a su baja transparencia de Secchi, la dominancia de Cyanobacterias y la condición anóxica casi permanente en las partes profundas del lago. Se observó un cambio en la proporción de N a P, lo que indica que hay una variación en el factor limitante principal a lo largo del año. El N llega a ser limitante durante la época seca, cuando la entrada de este elemento probablemente disminuye debido a la reducción del volumen de agua de escorrentía superficial, añadido a una mayor entrada de P desde los sedimentos en el periodo de mexcla profunda. El P ejerció una limitación más severa de acuerdo al valor de la proporción N/P. El fitoplancton compuesto por 58 especies de algas, estuvo dominado por Cyanobacteria y Chlorophyta. Sólo algunas pocas especies dominaron la comunidad, lo que redundó en bajos valores de diversidad. El zooplancton también mostró una pobreza de especies, con sólo siete especies encontradas en el lago. Hubo indicaciones de que el zooplankton realiza migraciones verticales en el lago.

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