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Water chemistry and trophic state of eight lakes in Costa Rica[1]

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Introduction

This paper is a contribution to the growing body of information on the freshwater resources of Costa Rica. The data set was collected in 1986 from seven Costa Rican lakes that lie within Chirripó National Park, La Amistad National Park or Barbilla Biological Reserve, and a hydropower reservoir (Fig. 1). Our purpose was to contribute to a resource inventory of these areas by documenting limnological conditions in the photic zone of these remote waterbodies. The analysis emphasizes ionic salinity, lake trophic state and major algal taxa.

Site descriptions

Laguna Grande (3520 m), Chirripó National Park, is located in paramo vegetation in the Valle de los Lagos of the Cordillera Talmanca (Pacific side) near Cerro Chirripó (Fig. 1). GOCKE et al. (1981) estimated the volume of this glacial lake as 468,000 m³, and HORN (1989) studied its sediments to assess fire history in the watershed. We also sampled two smaller lakes in the adjacent valley (Atlantic side). The lake referred to as Lago de las Morrenas # 1 is most likely the lake sampled by LÖFFLER (1972) and drains into Lago de las Morrenas # 2. At the time we sampled the outlets of Laguna Grande and Lago de las Morrenas # 1 were active. These three lakes are among the some 30 cirque lakes in this region (LÖFFLER 1972). HORN (1990) estimated that ice last retreated from this region some 10,000 years ago.

Lakes Dabagri, Dorotiri, and Sacabico are located in tropical rain forests in a drainage near the border of La Amistad National Park. The lakes are at about 1050 m in a valley of the Río Llei, a tributary of the Río Telire (Fig. 1). We estimated these lakes are 2 ha (Dorotiri and Sacabico) to 8 ha (Dabagri). Each of these waterbodies had dead trees standing in them; evidence that they were formed or modified by recent tectonic activity (presumably local subsidence). At the time we sampled, Lago Dorotiri was covered with a dense layer of *Lemna* sp. and *Wolfia* sp.; these plants were less dense in Lago Sacabico.

Lago Ayil, located at about 480 m, lies within tropical rain forest on the Rio Moravia, a tributary of the Rio Chirripó del Atlántico (Fig. 1). This lake lies at the southern border of the Barbilla Biological Reserve. The map for this region (1 : 50,000, Barbilla 3545 IV) shows Lago Ayil being about 30 ha and that the Río Moravia flows through the lake. When we sampled, however, the lake was obviously much smaller than the map suggests. Local indigenous people told us that several years before our visit the lake area decreased following an earthquake. We presume that this tectonic activity altered the waterfall at the outlet.

Laguna de Arenal, located at 540 m in a volcanic region in north central Costa Rica, is a hydropower reservoir that was completed in 1979 by modifying an existing lake. It has an area of 8092 ha and a mean depth of 21 m.

Methods

We began by sampling Laguna Grande de Chirripó on 29 August 1986 and completed our field work on 16 September by sampling Lago Ayil. This period is within the rainy season in Costa Rica. With the exception of Laguna de Arenal, we traveled to each lake by foot and sampled from an inflatable boat. We sampled two sites on Laguna de Arenal and one site on each of the other lakes. Water samples were filtered in the field for algal chlorophyll and suspended solids (nonvolatile = NVSS and volatile = VSS), and aliquots were transferred to glass tubes for subsequent nutrient analyses. Field measurements were made for alkalinity, color, pH, and oxygen. Water chemistry analyses were conducted at the University of Missouri using standard methods (APHA 1985).

Results and discussion

Ionic salinity and composition

Ionic salinity in these Costa Rican lakes (Table 1) ranged from < 10 to > 170 % of the world average for freshwaters (2.8 meq · l^{-1}, WETZEL 1983). The lowest values were measured at Chirripó where plutonic rocks predominate (granodiorite). Our conductivity and alkalinity measurements from Laguna Grande are each 40 % lower than measurements by GOCKE et al. (1981) during the dry sea-

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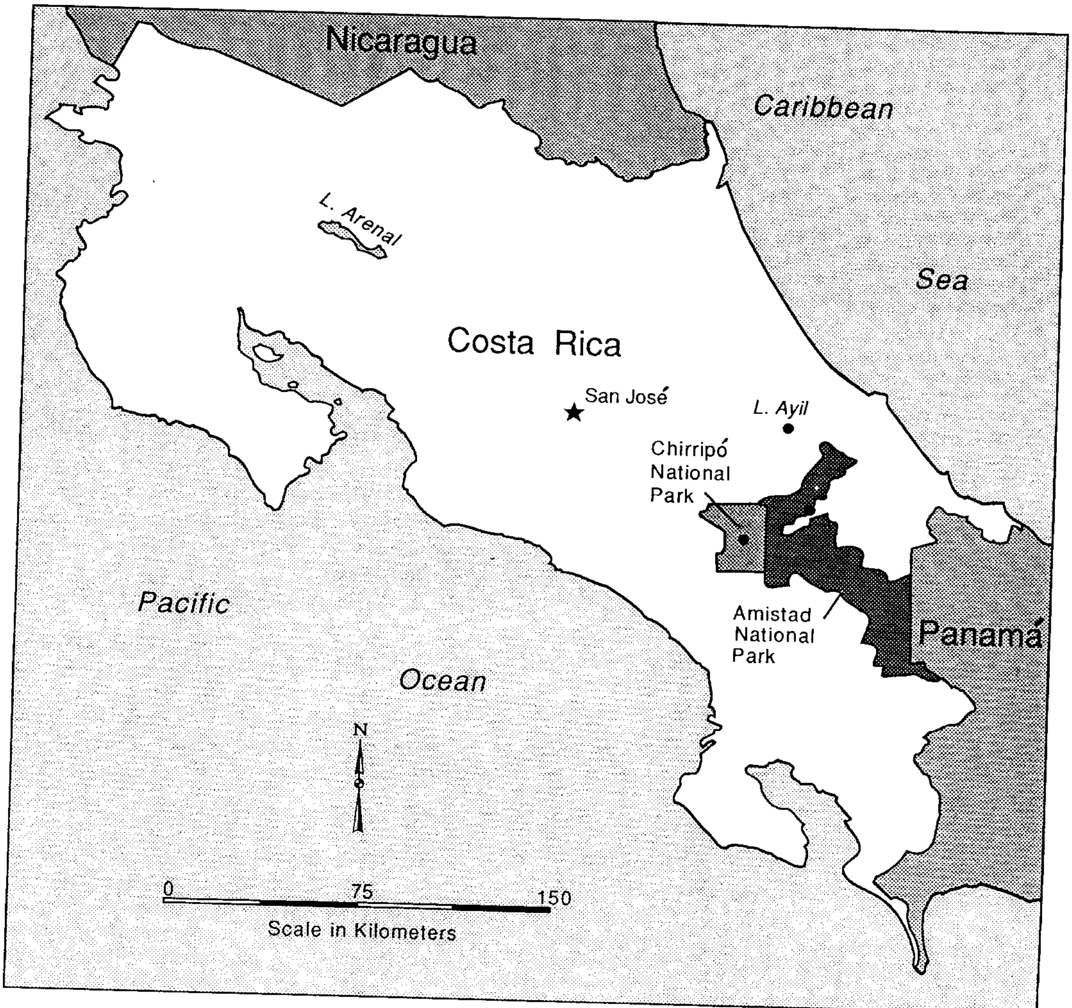

Fig. 1. Map of Costa Rica with dots showing the general location of the lakes sampled. See tables and text for lake names. Map prepared by the Geographical Resources Center, University of Missouri.

son; our collection was during the rainy season, and presumably this difference is the result of dilution. Löffler (1972) reported similar values from these lakes. These dilute lakes were slightly acidic (Table 1). Dissolved substances were highest in lakes located in tropical forest valleys in the La Amistad National Park (Table 1) where forest soils were rich. Salinity was intermediate in Lago Ayil, a riverine, lake, and in Laguna de Arenal where soils are developed from volcanic ash (Table 1).

The prevailing mineral composition of the Costa Rican lakes was dominated by Ca and bicarbonate – with one exception, Ca comprised 50 % of the cations and bicarbonate accounted for 81–96 % of the anions (Table 1). In most lakes the Na equivalents matched or moderately exceeded that of Mg; this formulation is characteristic of water draining igneous materials (Wetzel 1983). Proportions of K, S and Cl were typically low in these lakes (Table 1). Löffler's (1972) data from the Chirripó Lakes showed more S and less Na than our samples.

The mineral composition of Laguna de Arenal differed somewhat from the others (Table 1). In this lake, Ca, Mg and Na were present in near equal proportions and Cl comprised 15 % of the anions. In the volcanic streams at La Selva,

Table 1. Ionic salinity and conductivity (KSP) data from Costa Rican lakes sampled in 1986; salinity expressed as the sum of cations and anions.

Region and Lake	KSP $\mu S \cdot cm^{-1}$	Salinity as $meq \cdot l^{-1}$	Ca	Mg	Na	K	HCO_3^-	SO_4-S	Cl	Color Pt Units	pH
			% of Cations				% of Anions				
Chirripó National Park											
Laguna Grande de Chirripó	8	0.167	54	24	22	<1	82	5	13	5	6.6
Lago de las Morrenas #1	11	0.220	50	20	29	1	81	12	8	5	6.8
Lago de las Morrenas #2	14	0.271	53	19	26	2	90	4	6	5	6.8
Barbilla Biological Reserve											
Lago Ayil	93	1.929	59	25	14	2	93	4	3	15	7.4
La Amistad National Park											
Lago Dabagri	208	4.741	58	16	25	1	96	3	1	10	8.4
Lago Dorotiri	202	4.804	56	17	26	1	96	2	2	–	7.8
Lago Sacabico	–	4.893	54	20	26	<1	94	5	1	–	8.6
Hydropower Reservoir											
Laguna de Arenal – South	100	1.855	39	31	26	5	80	5	15	5	7.9
Laguna de Arenal – North	99	1.872	37	31	28	4	80	5	15	5	7.5

Table 2. Limnological data from Costa Rican lakes sampled in 1986. Mean values of all samples are presented for unstratified lakes (stratify = N) and mean values of samples from the epilimnion are presented for stratified lakes (stratify = Y). Nonvolatile solids = NVSS and volatile solids = VSS.

Region and Lake	n	Surface °C	Stratify	TN	TP	Chl	SiO_2	NVSS	VSS	Secchi m
				$\mu g \cdot l^{-1}$			$mg \cdot l^{-1}$			
Chirripó National Park										
Laguna Grande de Chirripó	8	9	N	50	2	0.5	1.8	<0.1	0.4	>11.5
Lago de las Morrenas #1	7	11	N	165	3	0.5	3.5	<0.1	0.3	–
Lago de las Morrenas #2	5	11	N	150	3	0.6	4.5	0.1	0.4	–
Barbilla Biological Reserve										
Lago Ayil	6	23	Y	235	50	3.0	20.2	1.4	0.9	2.2
La Amistad National Park										
Lago Dabagri	5	26	Y	355	39	12.3	24.1	0.1	3.0	1.5
Lago Dorotiri	5	28.5	Y	540	81	1.9	25.5	–	–	2.2
Lago Sacabico	4	22.5	Y	515	24	3.4	19.0	–	–	1.7
Hydropower Reservoir										
Laguna de Arenal – South	10	24.5	N	215	11	4.1	24.3	0.6	0.9	4.0
Laguna de Arenal – North	10	24.5	N	170	10	4.2	22.1	0.5	0.9	3.8

Pringle et al. (1990) also measured high Na and Mg equivalents relative to Ca, and Cl comprised some 15 % of the anions.

Among these waterbodies there was a strong correlation ($n = 8$, $r = 0.78$) between Na and SiO_2 concentrations. This relation suggests mineral weathering (perhaps feldspar) was the major source of these constituents.

Trophic state

Our measurements (Table 2) show that the Chirripó Lakes were ultra-oligotrophic with low concentrations of nitrogen (TN), phosphorus (TP), algal chlorophyll (Chl) and volatile suspended solids. Water chemistry and algal biomass were nearly uniform with depth in these cold polymictic lakes (Löffler 1972, Gocke et al. 1981). Our nutrient measurements in Lago de las Morrenas # 1 match those by Löffler (1972) but his measurements in Laguna Grande were 3–4 times our values. The ratio of TN/TP in these lakes ranged between 25 and 55; indicating potential limitation by phosphorus (Forsberg & Ryding 1980). The predominant algal taxa are given in Table 3.

Table 3. Predominant phytoplankton (>5% of unit counts) in surface and subsurface samples from Costa Rican lakes.

Lake	Surface	Subsurface
Laguna Grande de Chirripó	*Selenastrum* sp. *Microcystis* sp. *Oocystis* sp. *Dactylococcopsis rhaphidioides*	*Selenastrum* sp. *Microcystis* sp. *Micractinium* sp. *Botryococcus* sp. *Dactylococcopsis rhaphidioides*
Lago de las Morrenas # 1	*Selenastrum* sp. *Oocystis* sp. *Chlorella* sp. *Staurastrum manfeldti* *Peridinium volzii* *Dactylococcopsis rhaphidioides*	*Oocystis* sp. *Peridinium volzii* *Dactylococcopsis rhaphidioides*
Lago Ayil	*Cryptomonas* sp. *Melosira* sp. *Oscillatoria* sp.	*Cryptomonas* sp. *Melosira* sp. *Gomphonema* sp. *Nitzschia* sp. *Closterium* sp. *Synedra* sp.
Lago Dabagri	*Peridinium* sp. *Nitzschia* sp. *Chroococcus* sp. *Oscillatoria limosa* *Anabaena flos-aquae*	*Cryptomonas* sp. *Pandorina morum* *Peridinium* sp. *Nitzschia* sp. *Chroococcus* sp. *Oscillatoria limosa* *Anabaena flos-aquae*
Lago Sacabico	*Chlorella* sp. *Nitzschia* sp. *Melosira granulata*	*Pandorina morum* *Cryptomonas* sp. *Melosira granulata* *Oscillatoria limosa* *Merismopedia* sp.

Bacterial counts showed the wet weight biovolume was 4.9 mg · m^{-3} at the surface of Laguna Grande, 3.3 mg · m^{-3} at 4 and 8 m, and 2.8 mg · m^{-3} at 12 m. Bacterial biovolume was 12.1 mg · m^{-3} and 3.6 mg · m^{-3} in the surface of Lago de las Morrenas # 1 and 2, respectively. These low bacterial biomass values are typical of ultra-oligotrophic lakes.

Lago Ayil was weakly stratified at the time we sampled. The surface temperature was 23 °C and between 2 and 8 m the lake was 21.5 – 21.0 °C and oxygen was >80% saturation in all samples. Nutrient concentrations in the subsurface samples were identical to surface values (Table 2). Chl was low given the nutrient levels; subsurface Chl averaged only about half the surface value and the algal communities in these two zones showed some differences (Table 3). Our assessment is that this lake is fed by phosphorus-rich river water (TN/TP = 5) that has a short residence time in the basin. During our field collections we detected a subsurface current flowing through the lake.

Lakes Sacabico and Dabagri were stratified at the time we sampled and each lake showed strong subsurface algal maxima associated with water that was >0.7 °C cooler than the surface (Figs. 2, 3). Judging from the Secchi transparency (Table 2), the upper boundaries of these subsurface layers (2 – 3 m) were within the photic zone and contained from 6 to 25 times the Chl pigment measured at the surface. Oxygen was present (O_2 >7 mg · l, 2 – 3 m) and these layers were nutrient-rich; TP was four times and TN was 1.7 – 3.2 times the surface value. The pigment composition (Knowlton et al. 1989) of the deepest samples from both lakes suggested that photosynthetic bacteria were present in anoxic water at the lower boundary of the peak. Samples collected from Lago Dabagri at 3 – 13 m were characterized by absorbance peaks at 770 nm. Our samples were col-

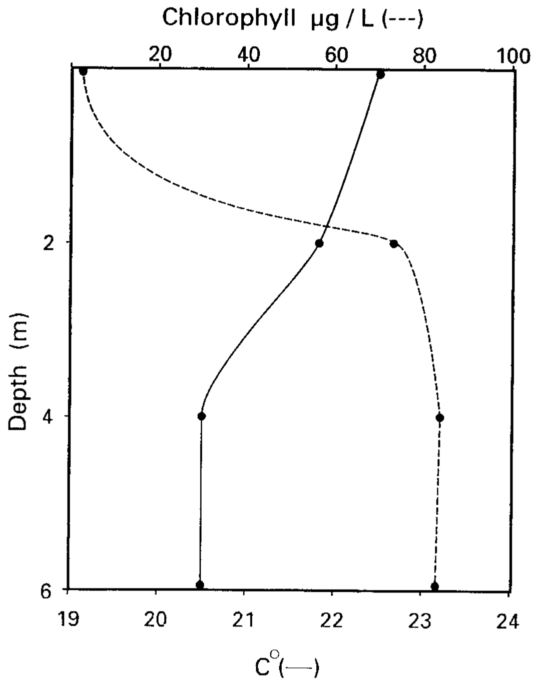

Fig. 2. Chlorophyll and temperature with depth in Lago Sacabico on 7 September 1986.

lected with a plastic bottle that integrated over a 0.5 m column of water; these measurements, therefore, do not show fine-scale vertical distribution of Chl and bacteria in relation to thermal stratification. At Lago Dabagri we collected two sets of samples to better describe vertical distribution of Chl in the stratified water column (Fig. 3 a, b).

Lakes in the La Amistad National Park were eutrophic, based on nutrients and Chl (Table 2). The ratio of TN/TP in Lakes Dabagri and Dorotiri was < 10, evidence of nitrogen limitation. And nitrogen fixing algae were among the predominant algal forms (Table 3). In Lake Sacabico TN/TP was > 20 in the surface water (Table 2) but at > 2 m this ratio was < 10, evidence that nutrient limitation switched from P to N within the water column. The major inflow to Lago Dorotiri had a TN/TP ratio of 4 on the day that we sampled. This measurement and the low N/P ratio in Riverine Lago Ayil suggest that runoff from tropical rain forests in this general region can be low in N relative to P. Pringle et al. (1986, 1990) have also found low N/P ratios in phosphorus-rich streams at various elevations in Costa Rica's Caribbean slope.

Based on nutrient and Chl values (Table 2) Laguna de Arenal was oligo-mesotrophic (Forsberg

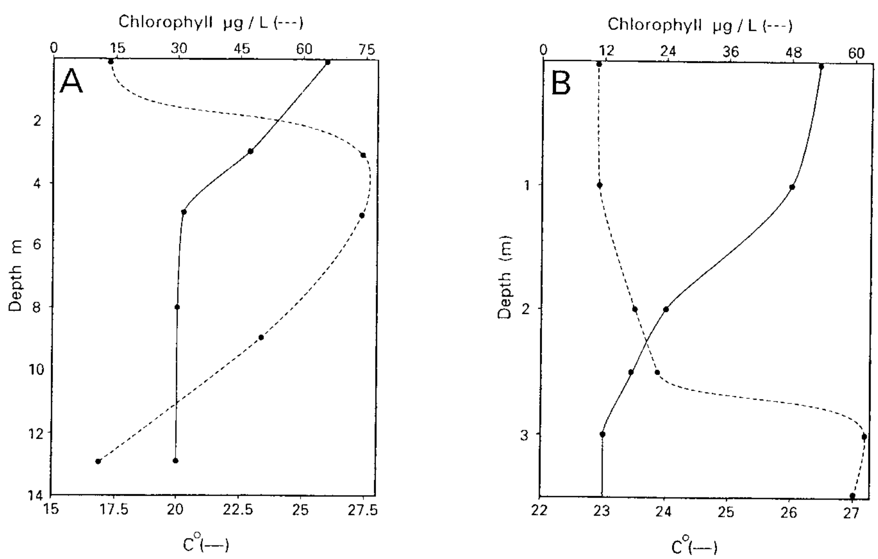

Fig. 3. Chlorophyll and temperature with depth in Lago Dabagri on 6 September 1986. Note that two collections were made on this date and the scales differ between panel A and B.

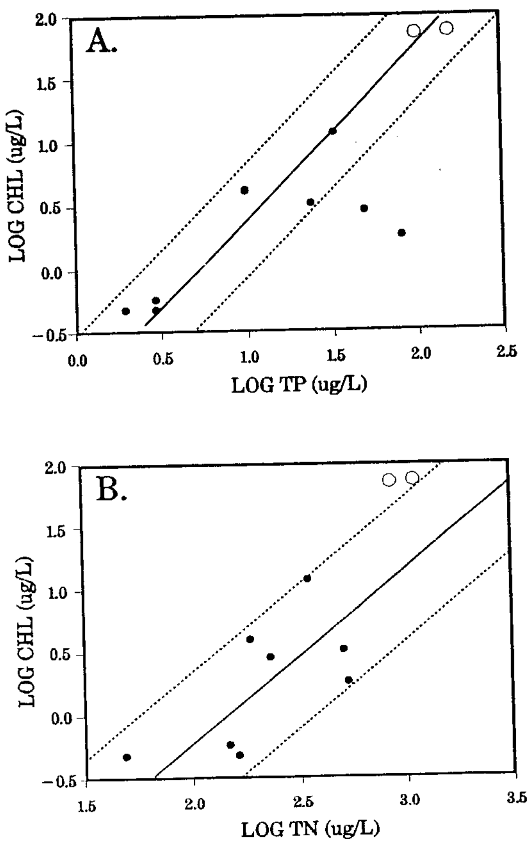

Fig. 4. Panel A: Chlorophyll and total phosphorus data from Costa Rican lakes (Table 2) plotted on the 95% confidence limits of the regression relation by Jones & Bachmann (1976). Panel B: Chlorophyll and total nitrogen data from Costa Rican lakes plotted on the 95% confidence limits of the regression relation by Canfield (1983). In both panels measurements from the subsurface algal peaks in lakes Sacabico and Dabagri are shown as open circles.

& Ryding 1980) at the time we sampled. Chlorophyll samples collected in November 1986 (by GUV) averaged 4.3 μg · l, and provide additional support for a mesotrophic classification. We sampled the southern end in the afternoon when there was < 1 °C difference in water at the surface and at 25 m but there were no noticeable differences in the distribution of chemicals or algal biomass in the water column; the following morning the water column was a uniform temperature at the north location. Oxygen ranged between 6 mg · l^{-1} and saturation in our samples. Ratios of TN/TP were 17–20, suggesting the lake was at the point where phosphorus limitation occurs (Forsberg & Ryding 1980).

Among most of these Costa Rican lakes, the yield of Chl per unit TP was within the confidence limits of the relation described by Jones & Bachmann (1976) for a broad range of temperate lakes (Fig. 4 a). Measurements from the subsurface algal peaks in Lakes Sacabico and Dabagri also fit this relation (Fig. 4 a). The exceptions were Lago Dorotiri, where the water column was heavily shaded by floating plants, and Riverine Lago Ayil, where algal biomass is likely affected by a brief water residence time. Nitrogen limitation was also a possible factor in these two waterbodies; they had the lowest TN/TP values in the data set (Table 2).

The yield of Chl per unit TN in the study lakes fits the relation by Canfield (1983) for Florida lakes (Fig. 4 b). Data from the subsurface samples in Lakes Dabagri and Sacabico were, however, slightly above the upper confidence limit of Canfield's relation.

Conclusions

Costa Rican lakes were not included in early limnological studies of Central America (reviewed by Cole 1963), so historical information on their water chemistry is lacking. Instead, characterization of the regional limnology of the country has occurred during the past two decades (Löffler 1972, Gocke et al. 1981, Pringle et al. 1986, 1990, Umaña 1990, Horn & Haberyan 1993, and others). Our data set contributes to that purpose and provides information on several lakes not previously sampled.

Among our major findings are: 1) dissolved solids in most waters sampled (Table 1) were primarily the calcium-bicarbonate type; 2) lake trophic state followed an expected gradient (Table 2) ranging from ultra-oligotrophic high-mountain lakes to eutrophic lakes in tropical rain forests; 3) subsurface chlorophyll maxima measured in two of the study lakes fit the general hypothesis for this phenomena (Moll & Stoermer 1982) and metalimnetic algal peaks can be expected in other stratified lakes in the region; 4) low TN/TP ratios in tropical forest lakes suggest N limitation and support earlier observations by Deevey (1957) of nitrogen deficiency in Central American lakes; and 5) the general fit of these data to published Chl-TP and Chl-TN relations (Fig. 4) suggests that algal-nutrient relations in Costa Rican lakes are similar to lakes elsewhere. These are tentative conclusions based on only a few samples collected during the rainy season. Collectively, however, the data set depicts existing conditions and provides a basis for hypothesis testing.

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