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Sediment characteristics of tropical, karst lakes and their relationship with watershed topography, lake morphometry, and human activities

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Abstract We analyzed multiple variables in recent sediments from 18 tropical, karst lakes in "Lagunas de Montebello" National Park, a Mexican Protected Natural Area and Ramsar site, to explore relationships between sediment characteristics and lake attributes: topography/location (mountain, surface-water-dominated vs. plateau, groundwater-dominated), morphometry (shallow vs. deep), and human activities (urbanization/agriculture). The study lakes fell into two groups: (1) pristine, oligotrophic, mostly located in the SE mountain terrain, and (2) impacted, eutrophic, in the NW plateau region. Sediment samples were collected from the central, deepest zone of each lake and analyzed for texture (grain size), carbonate content, and organic C and N. Water variables were measured in the water column overlying the sediment collection sites. Specific conductance, chlorophyll *a*, and total particulate carbon were higher in impacted, eutrophic plateau lakes than in pristine mountain lakes. Sediments, although composed mostly of silts, differed in grain size. Pristine, oligotrophic mountain lakes possessed coarser sediments, with a higher concentration of most likely recalcitrant organic carbon, than impacted, eutrophic plateau lakes. Topography/location is the primary factor that contributes to sediment differences, whereas eutrophication, caused by deforestation and agricultural runoff, is the second most important agent modifying sediment characteristics. The only pristine plateau lake, San José, had water quality similar to pristine mountain lakes, but finer sediments with lower organic C, N, and C/N. Comparison of San José sediments with those of impacted eutrophic plateau lakes indicated eutrophication has led to coarser sediments, as well as enrichment in CO_3, organic C and N. Eutrophication-related sediment characteristics are valuable variables that can be used in paleolimnological studies to identify the onset of lake eutrophication in tropical karst water bodies.

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Introduction

Lake sediments are depositional products and depend on transport and accumulation mechanisms controlled by regional and local factors that interact in complex ways (Cohen 2003). Superimposed on these natural controls, human impact has become an increasingly important factor influencing sedimentation and sediment characteristics during the last few millennia. Regional factors such as geology, climate, and topography are important controls on sediment export from the landscape to lakes. In-lake factors such as morphometry, trophic status, and lake mixing patterns also control sediment accumulation and diagenesis (Killops and Killops 2005). As lacustrine sediments represent important paleoenvironmental archives, a better understanding of the modern processes that control sediment transport and accumulation in lakes is fundamental to improve paleoenvironmental inferences and our ability to differentiate natural from anthropogenic sediment characteristics.

Location and topography exert a first-order control on mass-wasting rates, resulting in generally higher sediment loads in lakes located downstream from mountainous areas. Rock properties define sediment mobility, with the mobility of sedimentary rocks exceeding that of crystalline rocks by a factor of 1.4 (Dedkov and Mozzeherin 1996). Topography and rock properties control sediment discharge to the lake by modulating the proportion of water inflow through surficial runoff, in contrast to groundwater discharge. Vegetation cover in a basin is also a great modulator of sediment delivery to lakes, and human-induced land-use changes frequently lead to greater erosion and sedimentation (Duru et al. 2017).

Grain size is a fundamental property of sediments and provides important clues for reconstructing the transport history and depositional conditions associated with catchment disturbance events and human impact (Itam et al. 2017). It is important in sediment–water interactions (e.g. phosphorus deposition and release), and thus influences relevant limnological processes such as eutrophication. Morphometry defines to a great extent the circulation pattern (thermal stratification and mixing) in a lake, which in turn can affect sediment accumulation, by controlling the availability of hypolimnetic oxygen, and therefore the rate of organic matter accumulation and decomposition.

Lagunas de Montebello National Park (LMNP) is a karstic lake district in southern Mexico (Fig. 1) with more than 60 solution lakes whose limnological characteristics are still poorly known, despite their location in a national park and status as a Ramsar site (*Lagunas de Montebello*). Local inhabitants of the LMNP claim that since 2003 several changes have occurred in the lakes, particularly those on the NW plateau. Such changes included a shift in water color from crystal clear to yellow-green, with the presence of a yellow–white supernatant, fetid odors from sulfur compounds, and fish die-offs. Paleolimnological research undertaken in Lake Balantetic (also known as Balamtetik), on the NW plateau, showed a history of recurrent human impacts, with evidence of deforestation and wastewater input from the Rio Grande de Comitán since the 1950s, but with particularly intense anthropogenic disturbance during the decade from 1990 to 2000 (Caballero et al. 2019).

As a result of recent human activities, most study lakes on the NW plateau, except one named San José, are turbid and eutrophic, i.e. "impacted." In contrast, most SE mountain lakes are pristine, and have clear, oligotrophic waters. This begs the question as to what degree anthropogenic influences affect sedimentation processes and characteristics in this region with complex topography and different lake morphometries. Specifically, we sought to address whether lake sediment granulometry and organic carbon content could be used to identify whether these karst water bodies were subject to human disturbance.

We measured water and sediment variables in the main water bodies of the LMNP, to better understand the relative importance of factors that control trophic state and sedimentation processes in this karst lake district, such as location and topography (SE mountain lakes vs. NW plateau lakes) and lake morphometry (shallow vs. deep lakes), and establish current, in some cases baseline conditions, which will be useful for future paleolimnological studies in the area. Considering that human impacts on some Montebello lakes have been ongoing since the 1950s, we also sought to identify how cultural eutrophication has, and is
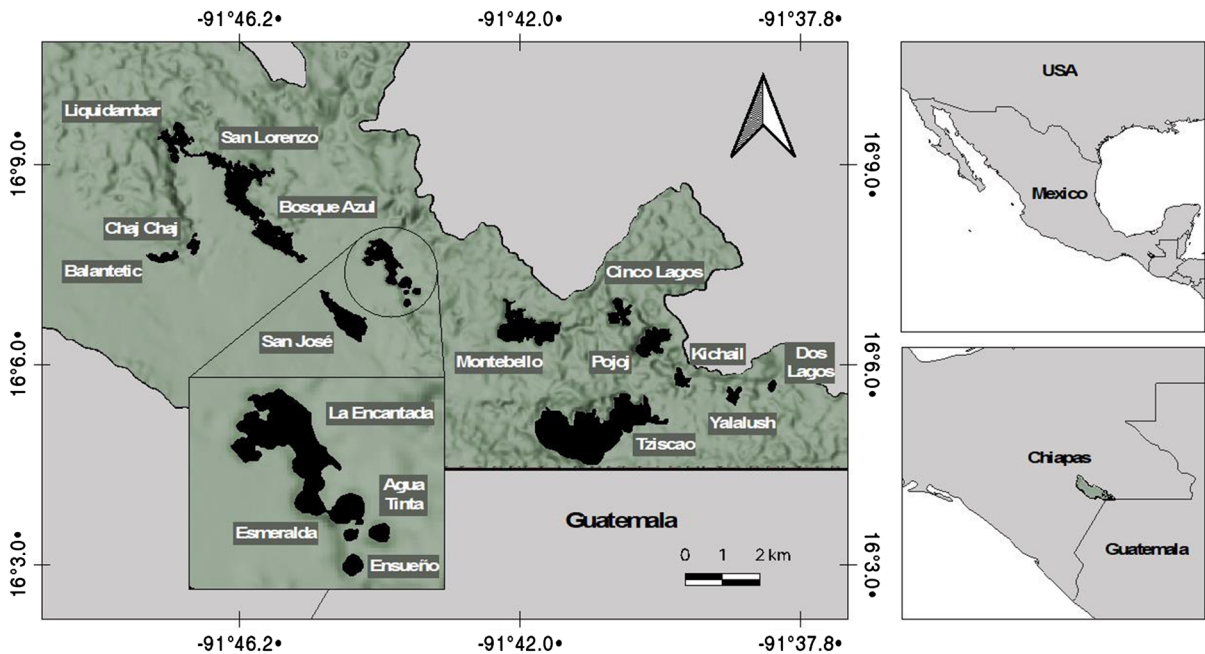
Fig. 1 The "Lagunas de Montebello" National Park (LMNP) lake district, Chiapas, Mexico. Lakes considered in the study are labeled. The Digital Elevation Model (DEM) used corresponds to the Mexican elevation continuum [version 3.0, resolution 15 m × 15 m; obtained from Instituto Nacional de Estadística y Geografía (INEGI) 2013]

altering water and sediments in these lakes, and to compare their characteristics with those of lake systems that remain pristine.

The lakes selected for study include all the lake types found in the LMNP and provided a unique opportunity to test several hypotheses:

- Since plateau and mountain lakes belong to the same lake district, they originally had very similar water quality, though the surface-fed (Río Grande de Comitán) plateau lakes display poorer water quality (i.e. higher trophic state) than groundwater-fed mountain lakes subjected to soil erosion and agricultural/urban pollution.
- Both mountain and plateau lakes possess allochthonous, terrigenous sediments, however plateau lakes receive sediments directly from the Río Grande de Comitán. Those sediments are transported over long distances in the drainage basin and include material from agricultural and urban source areas.
- Steep slopes surrounding mountain lakes accelerate transport of sediment, which travels only short distances before reaching the lakes, leading to coarser sediments than in plateau lakes, which are

surrounded by gentle slopes and receive sediment that has traveled long distances in a lower-energy environment.
- Shallow lakes should have coarser sediments, eroded and transported into the lakes from the riparian landscape. In comparison, sediments from the center of deep lakes should be finer, because coarse sediments are deposited close to the shoreline.
- Eutrophication of most plateau lakes leads to finer, highly organic sediments derived from autochthonous sources with high rates of primary production and low organic matter remineralization rates, but also from allochthonous sources such as agricultural soil erosion, and are enriched in N (smaller C/N) from agricultural fertilizers and untreated wastewater.

Study area

The LMNP is near the border between Mexico and Guatemala, in the central plateau of Chiapas. It has an area of 64.26 km^2 and extends from 16° 04′ 40″ to 16° 10′ 20″ N and from 91° 37′ 40″ to 91° 47′ 40″ W

(Fig. 1). Local geology is dominated by Cretaceous limestone and shallow dolomite platform deposits, Paleocene turbidites, and Eocene to Miocene continental clastic deposits (Witt et al. 2011) (Fig. 2a). The lakes are located in the lower part of a well-developed karst area, between folding morphologies with mesiform structures and vertical karstic development, low elevations with sinkhole karst with slopes of 11–57°, and karst plain (Mora et al. 2016).

The lakes are aligned in a NW–SE orientation (Durán Calderón 2013) and include dolines, uvalas, and poljes. They display a wide array of morphometries (Alcocer et al. 2016a). There are poorly developed soils (e.g. Leptosols) in the steepest, upper part of the sub-basin. Phaeozems dominate in the plateau area, whereas there are Luvisols and Leptosols around the lakes (Martinez 2015) (Fig. 2b).

The region's climate is temperate, humid, with precipitation concentrated in summer; however, more than 10% of the annual precipitation falls during the winter. It is an isothermal (mean annual temperature variation < 5 °C) climate of the Ganges type (Köppen type Cb(m)(f)ig, García 1988). Mean annual temperature, precipitation, and evaporation are 17.3 °C, 2279 mm, and 948 mm, respectively (SMN, Tziscao meteorological station, 16.1° N, 91.63° W; 1475 m asl).
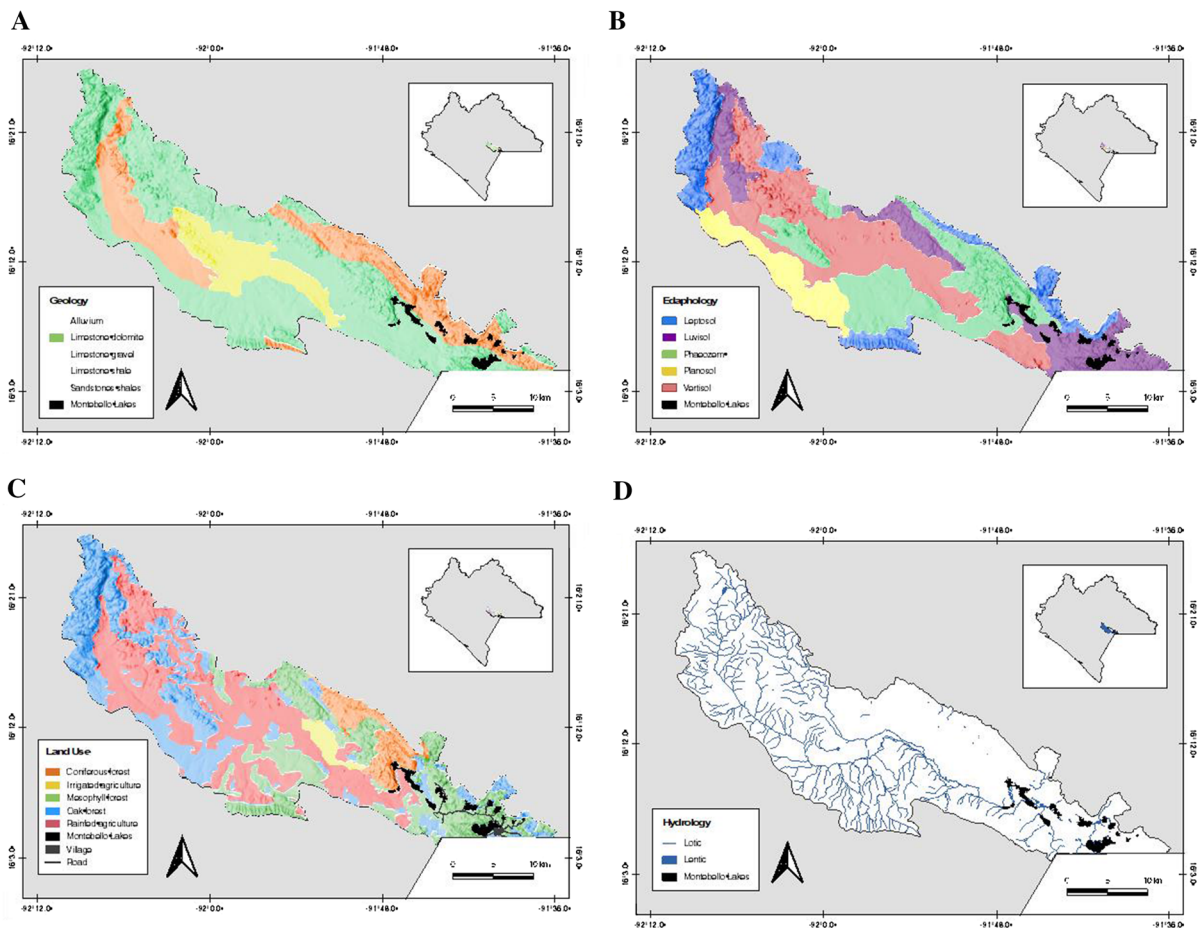
Fig. 2 Geology (**a**), soil type (**b**), vegetation and land use (**c**), and hydrology (**d**) of the Rio Grande de Comitán sub-basin. Spatial information obtained from: **a** Geological Mining Chart (Servicio Geológico Mexicano 2008); **b** vector data set on Edaphology scale 1:1,000,000 [Instituto Nacional de investigaciones Forestales y Agropecuarias (INIFAP)-Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO) 2001]; **c** vector data set on land use and vegetation scale 1:250,000, series V (INEGI 2013); and **d** Hydrographic Network scale 1:50,000, edition 2.0, hydrographic sub-basin RH30Gl R. Comitán/Cuenca R. Lacantún/R.H. Grijalva-Usumacinta (INEGI 2010)

The predominant vegetation of the LMNP is temperate forest (Fig. 2c). The main plant associations are coniferous forest (*Pinus oocarpa, P. maximinoi*), broad-leaved forest (*Liquidambar styraciflua*), mountain mesophilic forest (e.g. *Podocarpus matudae, Quercus benthamii, Q. laurina* and *Clethra mexicana*), littoral vegetation (*Typha, Phragmites communis*), secondary vegetation (*Simsia*) and agricultural crops (National Forest Inventory 2009–2014, CONAFOR 2018).

The LMNP lies at the lower end of the Río Grande de Comitán sub-basin, which is part of the larger Grijalva-Usumacinta hydrological region (RH30) (Fig. 2d). The Río Grande de Comitán discharges directly into Lake Balantetic, the first water body at the NW extreme of the LMNP. As mentioned, the lakes are divided into two groups (Durán Calderón et al. 2014). The first are the plateau lakes at lower altitudes (1400–1500 m asl) in the flat NW zone. These lakes are fed mainly by the Río Grande de Comitán and are connected hydrologically by artificial channels, likely constructed > 500 years ago for transportation purposes (Durán et al. 2014). They form a chain of lakes (Balantetic, Chajchaj, Liquidambar, San Lorenzo, Bosque Azul, and La Encantada) along a fault and fracture system. The second group includes the mountain lakes, which are found at higher altitudes (1500–1600 m asl) in the mountainous SE zone. These lakes are hydrologically isolated with respect to surface waters, and are fed mostly by groundwater, through caverns developed along the regional fault and fracture systems.

Most lakes in the LMNP are deep (z_{mean} > 10 m), warm monomictic lakes that circulate in winter, but remain thermally stratified in summer. Some shallow lakes, however, are polymictic and circulate episodically, throughout the year. With respect to trophic state (Vera-Franco et al. 2015), LMNP lakes are divided into pristine water bodies with clear, blue waters and low chlorophyll *a* concentrations (oligotrophic), and impacted lakes, with turbid, green waters and higher chlorophyll *a* concentrations (eutrophic). Plateau lakes receive hydrologic input from multiple point sources (river and urban sewage) and diffuse sources (agricultural runoff discharges). Importantly, some receive inflow from the Río Grande de Comitán, and runoff from abundant agricultural areas on the NW plateau. These source waters are very likely related to the documented eutrophication of lakes on the plateau. Indeed, all impacted lakes in the LMNP are plateau-lakes (Vera-Franco et al. 2015). In addition, abrupt, heavy rainfall associated with seasonal tropical storms, leads to flooding that disperses pollutants among the plateau lakes (Alcocer et al. 2018).

Materials and methods

We selected 18 study lakes (Fig. 1) within the LMNP, which represent the range of lake types in the region (Electronic Supplementary Material [ESM] Table S-1) with respect to location and topography (SE mountain or NW plateau, Durán Calderón et al. 2014), lake morphometry (shallow, polymictic or deep, warm monomictic (Alcocer et al. 2016a, 2018), and anthropogenic impact (pristine/oligotrophic or impacted/eutrophic (Oseguera and Alcocer 2015; Alcocer et al. 2016b, 2018; Vera-Franco et al. 2015; Rivera-Herrera et al. 2019). We sampled surface sediments from a central, deep location in each lake, during the warm and rainy season (May–June 2014), when warm monomictic lakes were stratified, but warm polymictic lakes continued to circulate. We took *in situ* water column measurements, and collected water and surface sediment samples for laboratory analyses.

Water

We collected *in situ* vertical profiles (1-m resolution) of temperature (accuracy: ± 0.1 °C, resolution: 0.01 °C), dissolved oxygen (accuracy: ± 0.1 mg L^{-1}, resolution: 0.01 mg L^{-1}), pH (accuracy: ± 0.2 U, resolution: 0.01 U), and specific conductance, standardized to 25 °C (K_{25}, accuracy: ± 0.5% of reading, resolution: 0.001 mS cm^{-1}), using a multi-parameter Hydrolab DS5 sonde deployed at the central, deepest zone of each lake. Values from the deepest 5 m were averaged to characterize bottom waters.

Water samples for chlorophyll *a* (Chl-a) and total particulate carbon (TPC) concentrations, which are proxies for algal biomass and the organic matter load reaching the sediments, were collected with a 5-L UWITEC water sampler, 1 m above the sediments. Samples for analysis of Chl-a concentration were passed through a Whatman 0.7 μm (GF/F) filter. After filtration, pigments were extracted from the filters

overnight, with 90% acetone at 4 °C. Samples were then analyzed with a Turner Designs TD10 AU fluorometer (EPA method 445.0, Arar and Collins 1997). Samples for TPC analysis were filtered through pre-combusted (550 °C, 4 h) Whatman 0.7-μm (GF/F) filters to eliminate any carbon traces. Filtration of the samples (Millipore stainless steel equipment) was carried out with a vacuum pump at 0.3–0.5 atm. TPC measurement was performed on a Carlo Erba model NC2100 elemental analyzer (Veronesi et al. 2002).

Sediments

Surface sediments from the central, deep portion of the lakes (see Alcocer et al. 2016a, b for detailed bathymetric maps) were collected with an Ekman dredge (0.0225 m^2). Five sediment aliquots were obtained with manual corers, taking care not to disturb the surface sediment layer. Two 1-cm^3 (L = 10 cm, Ø = 1 cm) sediment aliquots were taken for Chl-a concentration, and three 15-cm^3 (L = 10 cm, Ø = 3 cm) sediment aliquots were taken for analysis

of sediment grain size, carbonate, and elemental composition. All sediment subsamples were kept frozen in dark centrifuge tubes until analysis. The sediment sample from the mid-lake location was considered to be representative of lake-wide deposits. Most of the lakes in the LMNP have cylindrical morphometry, i.e. are "bucket-shaped" and possess little, shallow littoral area. Thus, most of the lake's bottom lies under relatively deep water. Moreover, Cortes-Guzmán et al. (2017) found no statistical differences in sediment grain size along bathymetric transects from the littoral to the deep zone of four Montebello lakes.

Sediment grain size was analyzed using a Beckman Coulter LS230 Laser Diffraction Particle Analyzer, and the principal texture parameters (mean grain size, sorting, skewness, kurtosis) were calculated and classified according to Folk (1980) and Wentworth (1922):

Mean grain size:

$$Mz\Phi = \frac{\phi 16 + \phi 50 + \phi 84}{3} \tag{1}$$

Table 1 Bottom water (i.e. bottommost 5 m of the water column) physical and chemical characteristics of the three lake categories: plateau (Plat) and mountain (Moun) lakes, shallow and deep lakes, and impacted/eutrophic (IE) and pristine/oligotrophic (PO) lakes

Characteristic	Plat	Moun	p	Shallow	Deep	p	IE	PO	p
T (°C)									
x	19.6	19.1		21.7	18.6	0.004	19.8	19.1	
s.d	1.7	1.5		1.0	0.8		1.8	1.5	
DO (mg L^{-1})									
x	0.0	0.8		2.2	0.0	0.003	0.0	0.8	
s.d	0.0	1.8		2.6	0.0		0.0	1.8	
pH									
x	7.2	7.1		7.3	7.1	0.007	7.1	7.1	
s.d	0.1	0.2		0.1	0.1		0.1	0.2	
K$_{25}$ (μS cm^{-1})									
x	689	386		555	489		744	386	0.021
s.d	263	350		282	370		240	350	
Chl-a (μg L^{-1})									
x	21.2	0.8	0.024	15.3	6.8		24.7	0.8	0.018
s.d	18.0	0.4		19.7	13.5		17.0	0.4	
TPC (μg L^{-1})									
x	3392	834	0.006	1665	1875		3830	834	0.002
s.d	1662	548		1313	1803		1304	548	

x, average; s.d. standard deviation, $p < 0.05$—only statistically significant differences are indicated

T temperature, DO dissolved oxygen, K$_{25}$ specific conductance, Chl-a chlorophyll-a concentration, TPC total particulate carbon
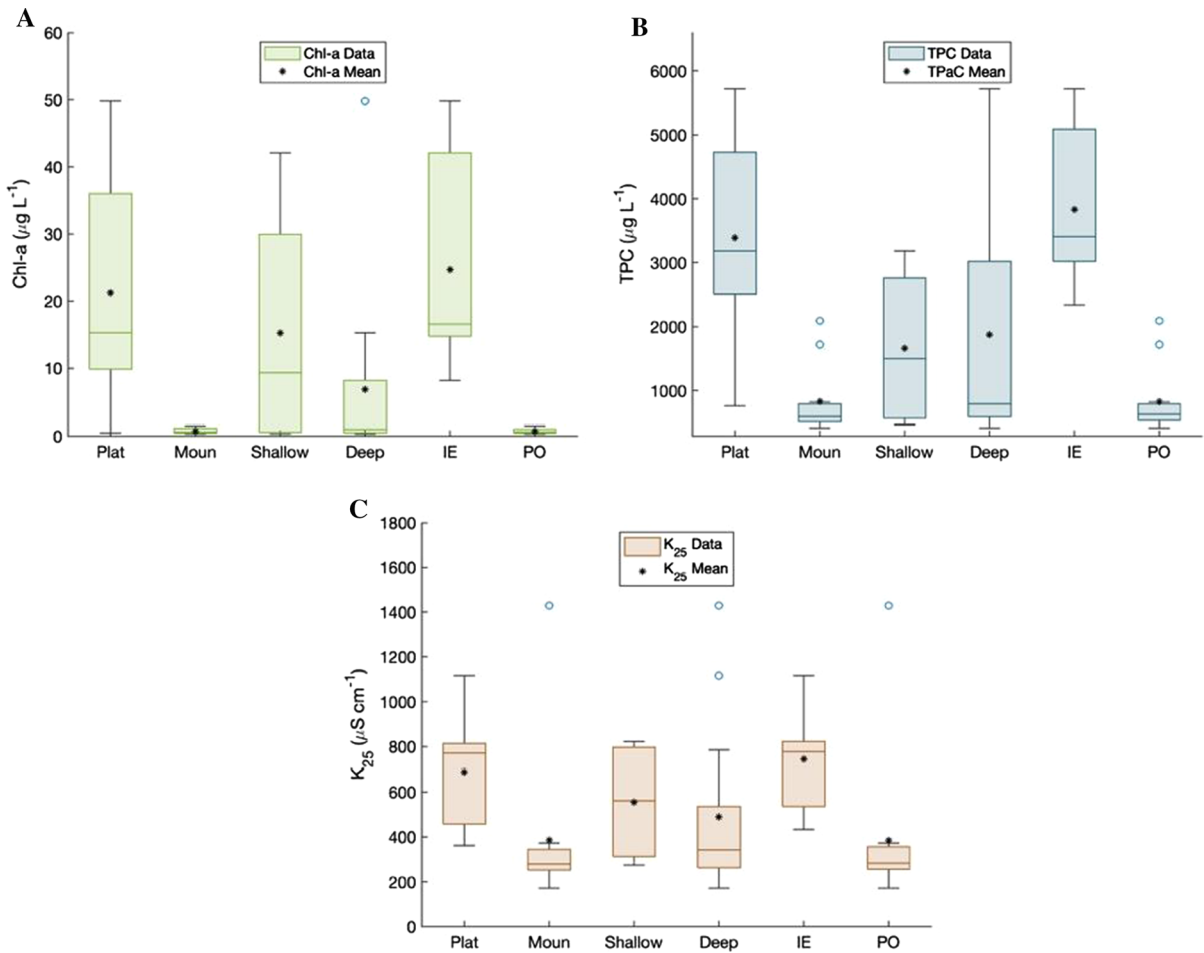
Fig. 3 Comparative boxplots of **a** chlorophyll-a (Chl-a), **b** total particulate carbon (TPC), and **c** electric conductance (K_{25}) for each lake group. (Plat = plateau, Moun = mountain, IE = impacted/eutrophic, PO = pristine/oligotrophic)

Sorting:

$$\sigma I\Phi = \frac{\phi 84 + \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6} \qquad (2)$$

Skewness

$$SkI = \frac{\phi 84 + \phi 16 + 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 95 + \phi 5 - 2\phi 50}{2(\phi 95 - \phi 5)} \qquad (3)$$

Kurtosis

$$KG = \frac{\phi 95 - \phi 5}{2.44(\phi 75 - \phi 25)} \qquad (4)$$

Samples for organic C (Corg) and N (Norg) determinations were run on dry, ground sediment samples and analyzed in a Carlo Erba NC2100 elemental analyzer at the USAII (Unidad de Servicio de Apoyo a la Investigacion y a la Industria), UNAM. %Corg and %Norg are reported on a sediment dry weight basis. Sediment carbonate content, reported as %CO$_3$ mass in dry sediment, was measured by weight loss after addition of 10% HCl and generation of CO$_2$.

Statistical analysis

Independent sample t-tests were performed to compare the water and sediment variables in the following pairs of lake types: (a) plateau versus mountain lakes, (b) deep versus shallow lakes, and (c) pristine/oligotrophic versus impacted/eutrophic lakes. To determine the similarity between lakes, cluster analyses (CA) were applied (linkage between groups, squared Euclidean distances) to group lakes with similar
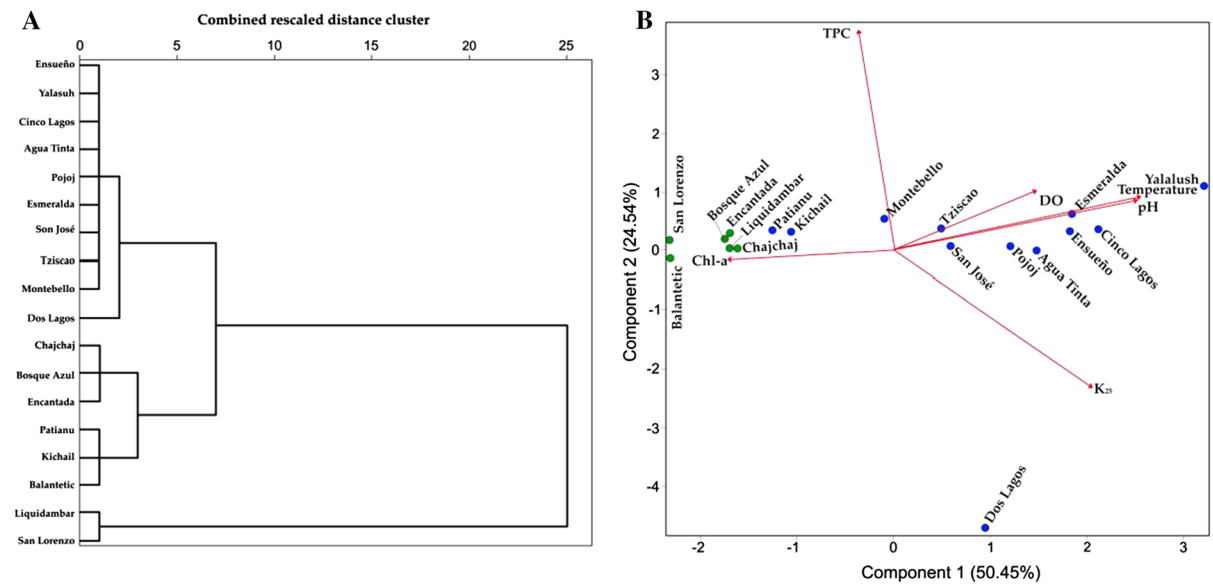
Fig. 4 Cluster Analysis Dendrogram (**a**) and PCA component 1 versus 2 plot (**b**) based on water quality characteristics of the Montebello lakes, Chiapas, Mexico. (T = temperature,

DO = dissolved oxygen, K_{25} = electric conductivity, Chl-a = chlorophyll-a concentration, TPC = total particulate carbon)

Table 2 Comparison (x = average, s.d. = standard deviation) of water characteristics of deep plateau (impacted/eutrophic) and mountain (pristine/oligotrophic) lakes with plateau, pristine/oligotrophic San José Lake

Water	T (°C)	DO (mg L^{-1})	pH	K_{25} (μS cm^{-1})	Chl-a (μg L^{-1})	TPC (μg L^{-1})
Plateau						
x	18.7	0	7.1	717	22.0	4366
s.d	0.9	0	0.0	305	18.8	1252
San José	**18.4**	**0**	**7.3**	**360**	**0.5**	**761**
Mountain						
x	18.5	0	7.1	402	0.8	893
s.d	0.8	0	0.1	389	0.4	593

T temperature, *DO* dissolved oxygen, *pH* pH units, K_{25} specific conductance, *Chl-a* chlorophyll *a* concentration, *TPC* total particulate carbon concentration

(a) water quality and (b) sediment characteristics. Likewise, a principal component analysis (PCA) was carried out to identify the characteristics that influence the ordering obtained with (a) water quality and (b) sediment characteristics. In the water quality PCA, variables that provided little information were removed. To perform the multivariate analyses (CA and PCA), data were "Z" transformed, so that high values did not bias the results and to keep values within an acceptable scale for comparison. All analyses were made with SPSS Statistics v24.

San José is the only plateau lake that has remained pristine/oligotrophic. We use San José as a reference (control) for non-impacted plateau lakes, assuming that conditions in San José are characteristic of the pre-disturbance conditions in the plateau lakes before they were anthropically impacted. San José's higher altitude, lack of surface connection with other plateau-lakes (it is groundwater-fed), and the fact that local inhabitants protect it so they have a source of potable water, are the likely reasons it remains pristine. We compared the water and sediment characteristics of San José with
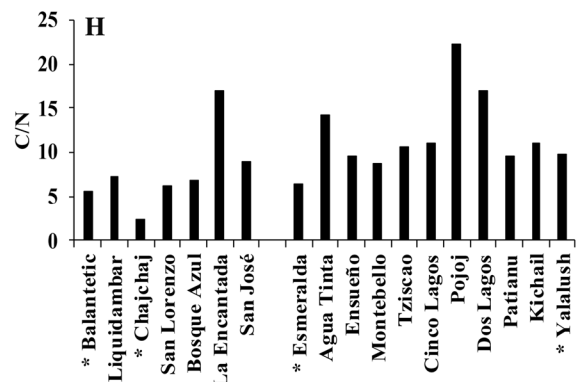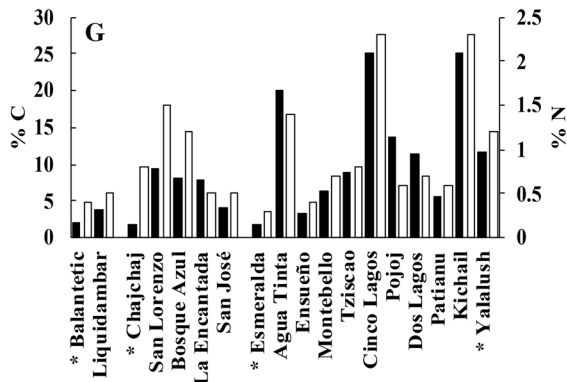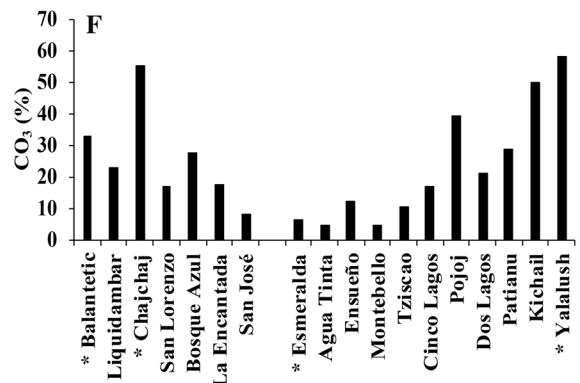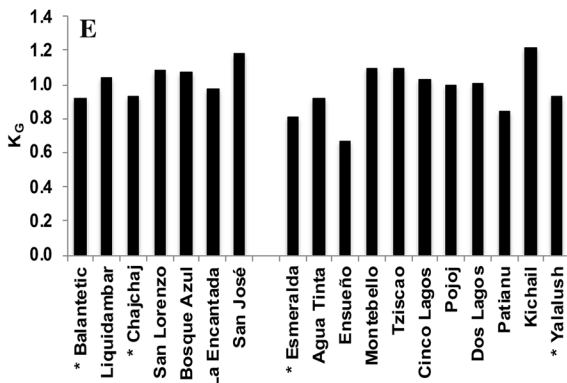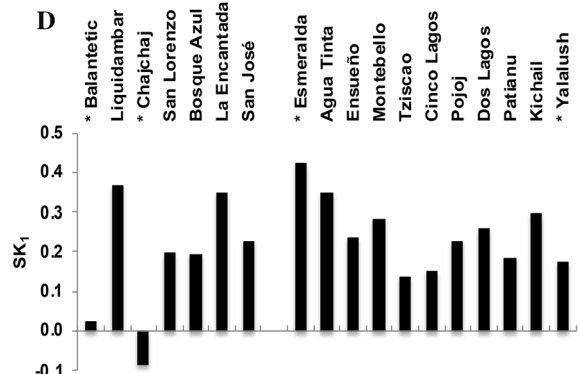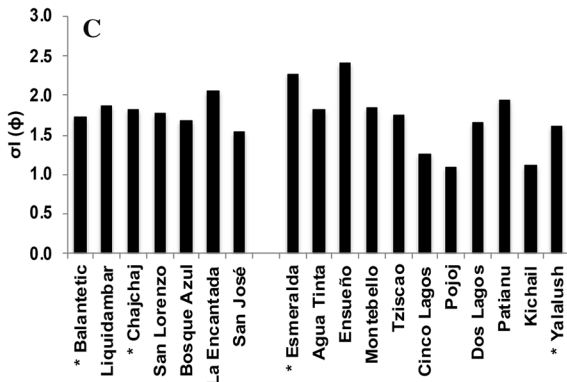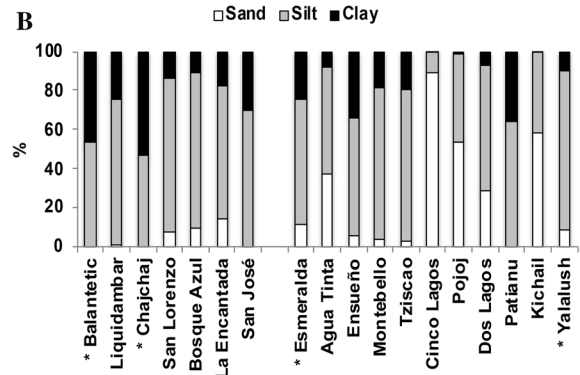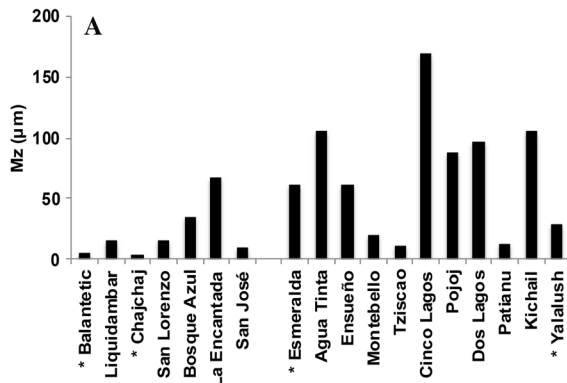
◀ **Fig. 5 a** Mean sediment particle size (μm), **b** sediment textural composition (%), **c** sediment particle sorting, **d** sediment asymmetry, **e** sediment kurtosis (K_G), **f** sediment carbonate content (CO_3), **g** sediment elemental composition (Carbon = black, Nitrogen = white), **h** sediment C/N ratio (%) along a NW–SE gradient of the Montebello Lakes. Plateau lakes on the left side, mountain lakes on the right side. (* Indicates functionally shallow, warm polymictic-lakes)

deep plateau (impacted/eutrophic) lakes and deep mountain (pristine/oligotrophic) lakes.

Results

Bottom waters

The main physical and chemical characteristics, including Chl-a and TPC concentrations in bottom waters (i.e. the deepest 5 m of the water column) of the Montebello lakes, are in ESM Table S-2. Some physical and chemical measures in the water overlying the sediments differed ($p < 0.05$) (Table 1) among all the three lake classes according to location (mountain or plateau), morphometry, circulation pattern (deep warm monomictic or shallow warm polymictic), and trophic state (pristine/oligotrophic or impacted/eutrophic).

Shallow lakes had higher temperature, pH, and DO compared to deep lakes. Only pristine/oligotrophic shallow lakes contained dissolved oxygen in the bottom waters; however, impacted/eutrophic shallow lakes and all deep lakes displayed anoxic bottom waters (Table 1). Chl-a and TPC concentration differed between plateau and mountain lakes, both being higher in plateau lakes. Impacted/eutrophic and pristine/oligotrophic lakes differed with respect to K_{25}, Chl-a, and TPC concentrations, as all three were higher in impacted/eutrophic lakes (Table 1, Fig. 3).

The CA (Fig. 4a) showed three groups at dissimilarity < 5. The first cluster contained 10 lakes, all of them pristine/oligotrophic. The second cluster had six lakes, four impacted/eutrophic and two pristine/oligotrophic (Patianú and Kichail) lakes. The third cluster possessed two impacted/eutrophic lakes.

The first two components of the water quality PCA (Fig. 4b) explained almost 75% of the variance. The first component (50.44%) was positively associated with temperature and pH and negatively with Chl-a, whereas the second component (24.54%) was positively associated with TPC and negatively with K_{25}. The lakes were separated into two groups. Lakes with higher temperature, higher pH, and higher concentration of Chl-a (impacted/eutrophic) aligned on the negative side of axis 1, whereas the lakes with the opposite characteristics (pristine/oligotrophic) were on the positive side. Pristine/oligotrophic Lakes Patianú and Kichail are positioned close to the impacted/eutrophic lakes, to the left in the diagram, based on their intermediate Chl-a concentrations. This is in accordance with the cluster divisions, and these lakes are grouped with the impacted/eutrophic lakes. Dos Lagos, with the highest K_{25} value, is an outlier lake on the second axis, according to the cluster analysis.

With respect to water characteristics (Table 2), San José was 67% similar to pristine/oligotrophic mountain lakes, whereas the other 33% of values were "unclear" (intermediate values between pristine/oligotrophic and impacted/eutrophic). These findings suggest that plateau lakes were originally oligotrophic, i.e. had crystal-clear waters, similar to mountain lakes. Older residents in the area confirm that the plateau lakes have changed and that cultural eutrophication has led to higher K_{25}, Chl-a and TPC concentrations.

Sediments

Particle size

The lakes with the coarsest sediments (> 100 μm, very fine or fine sands) were Cinco Lagos, Agua Tinta, and Kichail, all of them mountain, deep and pristine/oligotrophic, whereas the lakes with finer sediments (< 10 μm, fine silts) were Chajchaj, Balantetic and San José, all plateau lakes, the first two shallow and impacted/eutrophic, and the third deep and pristine/oligotrophic, (Fig. 5a Table SI-3). Sediments of the plateau lakes were significantly finer ($p < 0.05$) than sediments of the mountain lakes (Table 3).

Regarding grain-size proportions, there were statistical differences ($p < 0.05$) in sand proportions between plateau (5 ± 6%) and mountain (27 ± 29%) lakes, and between impacted/eutrophic (5 ± 6%) and pristine/oligotrophic (25 ± 29%) lakes (Table 3). Shallow and impacted/eutrophic lakes have silty-clay loam sediments, whereas deep and pristine/

Table 3 Sediment characteristics of the three lake categories: plateau (Plat) and mountain (Moun) lakes, shallow and deep lakes, and impacted/eutrophic (IE) and pristine/oligotrophic (PO) lakes

Characteristic	Plat	Moun	p	Shallow	Deep	p	IE	PO	p
Grain size Mz (μm)									
x	21.1	68.9	0.014	24.4	57.7		23.2	63.9	
s.d	22.5	49.5		26.7	49.4		23.9	50.4	
Sorting (φ)									
x	1.77	1.70		1.85	1.70		1.8	1.7	
s.d	0.16	0.43		0.29	0.36		0.1	0.4	
Skewness (SK$_1$)									
x	0.18	0.25		0.13	0.25		0.2	0.2	
s.d	0.16	0.09		0.22	0.07		0.2	0.1	
Kurtosis (K$_G$)									
x	1.03	0.96		1.03	0.96		1.0	1.0	
s.d	0.10	0.15		0.10	0.15		0.1	0.2	
Fractions (%)									
Sand									
x	4.7	27.2	0.030	5.1	22.2		5.4	24.9	0.043
s.d	5.7	29.2		5.9	27.6		5.9	28.9	
Silt									
x	67.0	58.3		61.3	61.8		66.6	59.2	
s.d	12.5	20.4		14.9	19.1		13.6	19.7	
Clay									
x	28.3	14.5		33.6	16.0		28.0	15.9	
s.d	16.3	12.9		19.9	12.1		17.8	13.2	
CO$_3$ (%)									
x	26.7	22.4		9.8	28.1		26.3	22.9	
s.d	17.5	17.5		5.0	17.2		19.1	16.8	
Elemental composition (%)									
C									
x	5.3	12.0	0.045	4.3	10.9		5.5	11.4	
s.d	3.1	8.2		4.8	7.5		3.3	8.2	
N									
x	0.8	1.0		0.7	1.0		0.8	1.0	
s.d	0.4	0.7		0.4	0.6		0.5	0.7	
C/N									
x	7.8	11.9		6.0	11.5		7.5	11.6	
s.d	4.5	4.5		3.0	4.6		4.9	4.3	

x, average; s.d. standard deviation, $p < 0.05$—only statistically significant differences are indicated

oligotrophic lakes have silty loams. Clay dominated in Chajchaj (53%), sands dominated in Cinco Lagos (89%), Kichail (59%), and Pojoj (54%), and silt dominated in the rest of the lakes (Fig. 5b, ESM Table S3).

Most lakes, plateau or mountain, shallow or deep, and impacted/eutrophic or pristine/oligotrophic, had poorly sorted sediments (Table 3). The lakes with better-sorted sediments (φ < 1.5) were Pojoj, Kichail, and Cinco Lagos, all of them deep and pristine/oligotrophic. Those with the most poorly sorted

sediments ($\phi > 2.0$) were Ensueño, Esmeralda, and La Encantada. These last three lakes are located in the transitional zone between the mountain and plateau lakes. Ensueño is deep and pristine/oligotrophic, Esmeralda is shallow and pristine/oligotrophic, and La Encantada is impacted/eutrophic (Fig. 5c, ESM Table S3).

Sediment particle size in most lakes was positively or very positively skewed (fine-skewed) (Table 3). The more positively skewed (≥ 0.3) lakes were Agua Tinta, Esmeralda, Liquidambar and La Encantada. The more symmetrical lakes (-0.1 to 0.1) were Balantetic, and Chajchaj (Fig. 5d). Most lakes were mesokurtic. Only pristine and deep Lakes San José and Yalalush were leptokurtic. Shallow and pristine/oligotrophic Esmeralda, and deep and pristine/oligotrophic Patianú and Ensueño were platykurtic and very platykurtic, respectively (Fig. 5e, ESM Table S3). Yalalush, San José, and Tziscao were more leptokurtic (fewer outliers), whereas Ensueño, Esmeralda, and Patianú were the more platykurtic, with a larger number of outliers (Table 3, ESM Table S3).

Carbonate content, organic fraction, and C/N ratio

The carbonate content (Fig. 5f, Table 3, ESM Table S3) of sediments in the Montebello lakes, did not differ ($p > 0.05$) between lake types, i.e. plateau or mountain, impacted/eutrophic or pristine/oligotrophic, shallow or deep. Lakes with the highest sediment CO_3 content ($\geq 50\%$) were plateau, impacted/eutrophic Chajchaj and mountain, pristine/oligotrophic Kichail and Yalalush. Lakes with the lowest sediment CO_3 content ($\leq 10\%$) were all pristine/oligotrophic lakes (Tziscao, San José, Esmeralda, Montebello and Agua Tinta).

Lakes with the highest sediment Corg content ($> 20\%$) were the deep, pristine mountain lakes Kichail, Cinco Lagos, and Agua Tinta. Those with the highest sediment Norg content ($> 2\%$) were pristine Kichail and Cinco Lagos. Lakes with the lowest amount of sediment Corg ($< 2\%$) were the pristine Esmeralda and the impacted Chajchaj; Norg ($< 0.5\%$) were the pristine Esmeralda and Ensueño, and the impacted Balantetic (Fig. 5g Tables SI-3).

Sediment Corg concentrations ($12.0 \pm 8.2\%$) in mountain lakes were statistically higher ($p < 0.05$) than in plateau lakes ($5.3 \pm 3.1\%$), whereas Corg in sediments of shallow and deep and impacted/
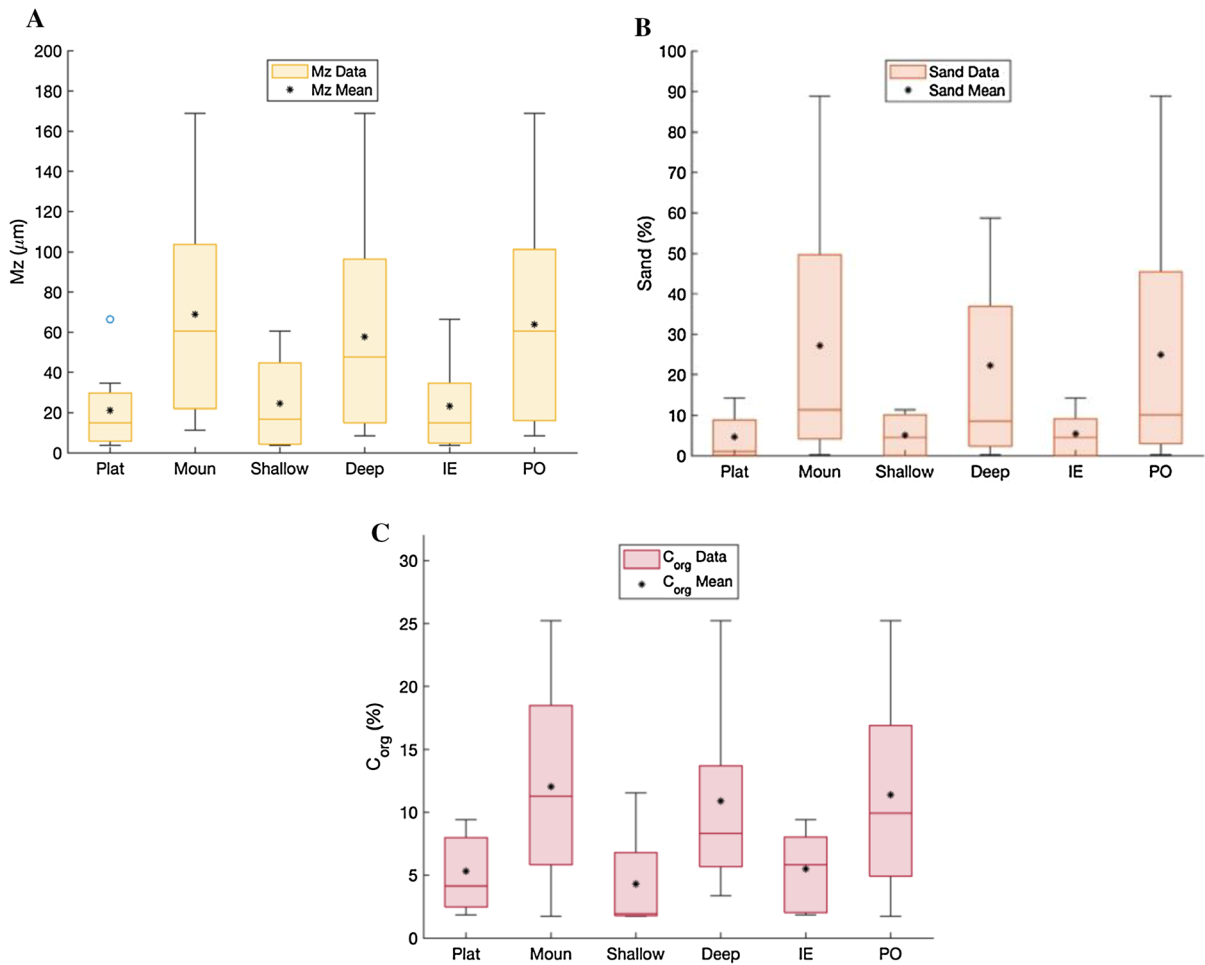
eutrophic and pristine/oligotrophic were not significantly different (Table 3). Sediment Norg content was not significantly different ($p > 0.05$) among the different lake types (Table 3). The lake with the lowest sediment C/N ratio was Chajchaj (2.3) and the highest sediment C/N ratio was measured in Pojoj (22.3) (Fig. 5h). The sediment C/N ratio was not statistically different ($p > 0.05$) among the different lake types (Table 3, Table SI-3).

Mean particle size, percent sand and Corg differed between plateau and mountain lakes, shallow and deep lakes, and impacted/eutrophic and pristine/oligotrophic lakes, all of them being higher in mountain, deep and pristine/oligotrophic lakes than in plateau, shallow, and impacted/eutrophic lakes (Fig. 6).

The CA (Fig. 7a) showed two groups at dissimilarity > 25; Cinco Lagos was separated from the other 17 lakes, which grouped close together. The larger group was further divided into two clusters at dissimilarity < 5. The first cluster consisted of 10 lakes, five pristine/oligotrophic and five impacted/eutrophic. The second cluster grouped the remaining seven lakes, six pristine/oligotrophic lakes, and one impacted/eutrophic lake.

The first two components of the PCA (Fig. 7b), based on sediment characteristics, explained 81% of the total variance. The first component (58.11%) showed a positive correlation with Corg content, mean grain size, and sand content in the sediments. Lakes with larger sediment grain size and higher percent sand and Corg content are located on the positive side of this component. The second component correlates positively with kurtosis, carbonate and silt content, and negatively with clay content. The lakes with the highest percent clay are found in the lower left of the diagram, whereas those with the highest carbonates, kurtosis, and percent silt plot on the positive side of this component.

The PCA confirmed the CA separation of Cinco Lagos from the rest of the lakes. Cinco Lagos is the lake with the coarsest mean sediment grain size and the highest percent sand. The other two clusters were also confirmed. Finer sediments with lower sand and Corg percentages characterized the cluster that included the most impacted/eutrophic lakes. The other cluster, composed mainly of pristine/oligotrophic lakes, showed coarser sediments and larger percentages of sand and Corg.

A

B

C

Fig. 6 Comparative boxplots of **a** mean particle size (Mz), **b** percentage of sands (S), and **c** organic carbon (Corg) per lake group of the Montebello Lakes. (Plat = plateau, Moun = mountain, IE = impacted/eutrophic, PO = pristine/oligotrophic)

With respect to sediment characteristics (Table 4), San José was 62% similar to impacted/polluted plateau lakes and 23% similar to pristine/oligotrophic mountain lakes, whereas 15% remained "unclear." This comparison suggests the main difference between the original pristine/plateau lakes, here represented by San José, and pristine mountain lakes, is that the former possess finer sediments, with lower percent sand, Corg, Norg, and C/N than the latter. Comparison of San José with the impacted/eutrophic plateau lakes indicates eutrophication has led to coarser sediments and enrichment in CO_3 and Corg and Norg.

Discussion

Bottom waters

Comparison of the different lake types showed that water temperature, DO concentration, and pH distinguished shallow from deep lakes, with all three variables higher in the shallow lakes. Lake thermal stratification was reflected in the bottom DO conditions of the two lake types, with anaerobic bottom water in the stratified, deep, warm monomictic lakes, and aerobic conditions in the water columns of shallow, oligotrophic, warm polymictic lakes. However, conditions in the eutrophic warm polymictic lakes, i.e. in which DO consumed by respiration > DO produced by photosynthesis, leads to

A

B
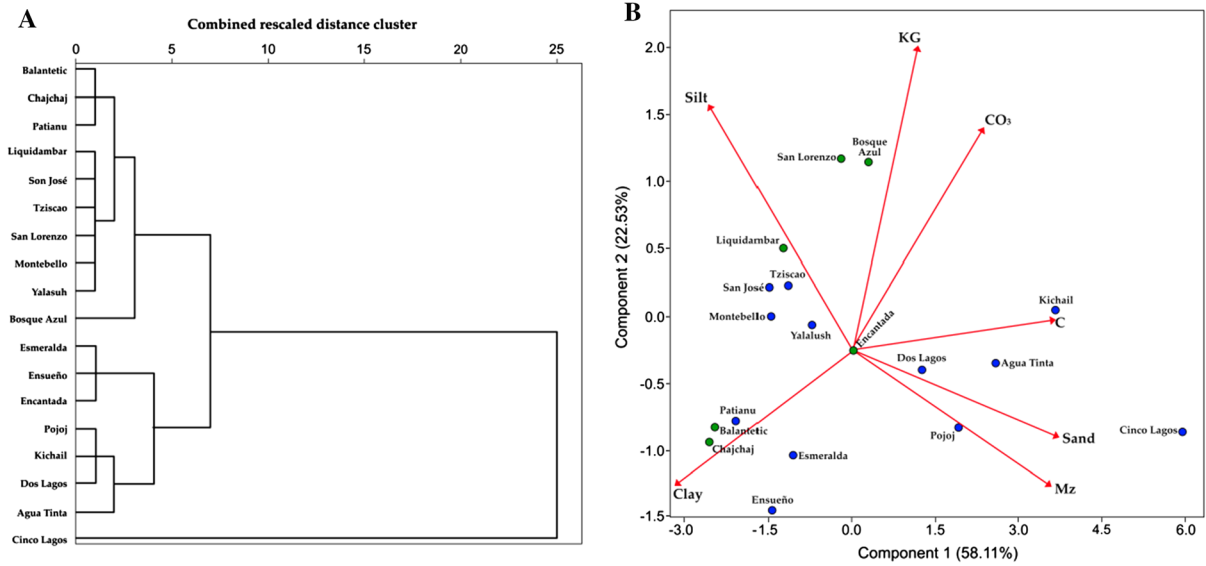
Fig. 7 Cluster analysis dendrogram (**a**) and PCA component 1 versus 2 plot (**b**) based on sediment characteristics of the Montebello lakes. (K_G = kurtosis, CO_3 = carbonates, C = Corg, M_Z = mean grain size)

Table 4 Comparison (x = average, s.d. = standard deviation) of sediment characteristics of deep plateau (impacted/eutrophic) and mountain (pristine/oligotrophic) lakes with plateau, pristine/oligotrophic San José Lake

Sediment	Mz μm	Sand %	Silt %	Clay %	σI ϕ	Sk1	K_G
Plateau							
x	33	8	75	17	1.8	0.3	1.0
s.d	24	5	5	6	0.2	0.1	0.1
San José	**9**	**0**	**69**	**31**	**1.5**	**0.2**	**1.2**
Mountain							
x	74	31	55	14	1.6	0.2	1.0
s.d	53	31	21	14	0.4	0.1	0.2

| Sediment	CO3	Elemental composition (%)		
	%	Corg	Norg	C/N
Plateau				
x	36.6	7.3	0.9	9
s.d	14.4	2.4	0.5	5
San José	**28.8**	**4.1**	**0.5**	**9**
Mountain				
x	24.6	13.2	1.1	13
s.d	18.6	8.3	0.7	4

Mz mean grain size, *σI* sorting, *Sk1* skewness, *K_G* kurtosis, *CO_3* carbonates, *Corg* organic carbon, *Norg* organic nitrogen

anoxia (Alcocer et al. 2018). Unfortunately, there are no shallow, pristine/oligotrophic plateau lakes left with which to compare. All such lakes have been subject to cultural eutrophication. It is likely, however, that with respect to water quality variables, unspoiled shallow and deep plateau lakes were quite similar to shallow and deep mountain lakes, respectively.

Chl-a and TPC concentrations were higher in plateau than in mountain lakes. Both variables are associated with the eutrophic status today characteristic of most plateau lakes. Indeed, K_{25}, Chl-a, and TPC concentrations make it possible to distinguish impacted/eutrophic lakes from pristine/oligotrophic lakes, all three variables being higher in the impacted/eutrophic lakes (Fig. 8). Higher concentrations of these variables indicate elevated primary productivity and/or organic matter pollution, both of which are occurring in the plateau lakes, except San José, in the NW region of the LMNP.

Analysis of the water column data enabled identification of cultural eutrophication and lake morphometry as important controls on water, each identified using three statistically different variables. Location (NW versus SE) and topography (plateau versus mountain) are statistically different in Chl-a and TPC concentration, and both variables are directly related to eutrophication. Thus, eutrophication becomes the most important controlling factor in
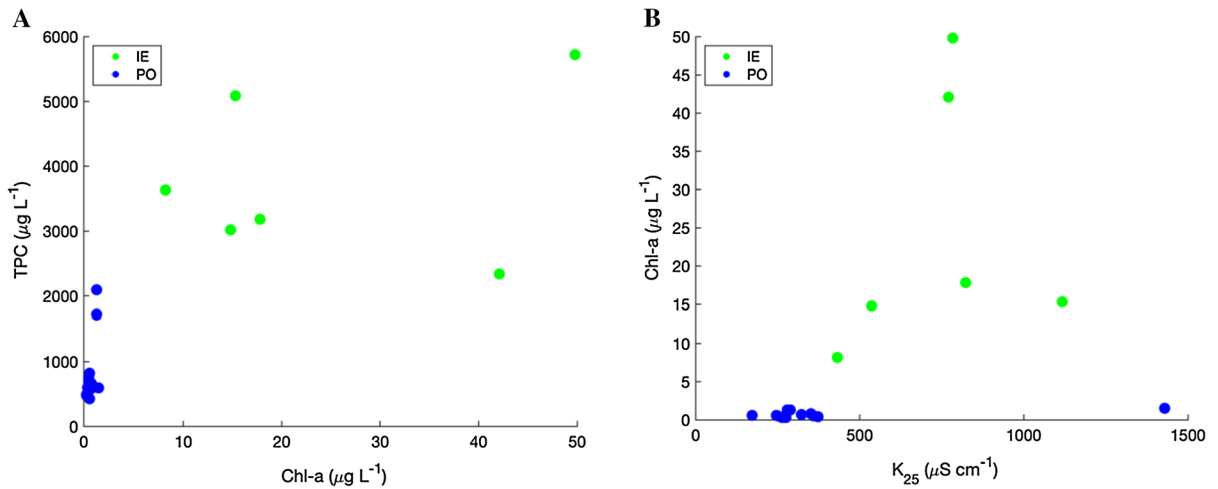
Fig. 8 Biplots of **a** chlorophyll-a concentration (Chl-a) versus total particulate carbon (TPC) and **b** electrical conductivity (K_{25}) versus chlorophyll-a concentration (Chl-a) in the Montebello lakes. (IE = impacted/eutrophic, PO = pristine/oligotrophic lakes)

defining the water quality of the lakes, followed by lake morphology.

Olea-Olea and Escolero (2018) found that nutrient concentrations in groundwater are high (2.36–18.13 mg NO_3-N L^{-1}, 0.02–0.20 mg PO_4-P L^{-1}) in the central plateau area, where the most intensive agriculture activity occurs. According to the groundwater flow network, all groundwater discharges into Lakes Tepancuapan and San Lorenzo, or the Rio Grande de Comitán. Mota (2019) identified shallow groundwater flow through the alluvial deposits in the basin that discharges into the Río Grande de Comitán and increases in potassium and N associated with use of agricultural fertilizers and septic tanks.

Sediments

Differences in sediment characteristics between the plateau and mountain lakes are statistically significant. Standard deviations of sediment characteristics of shallow and deep lakes are high, and thus they are not statistically different. The most critical sediment variables that enable differentiation between lake types are particle size, percent sand, and Corg content.
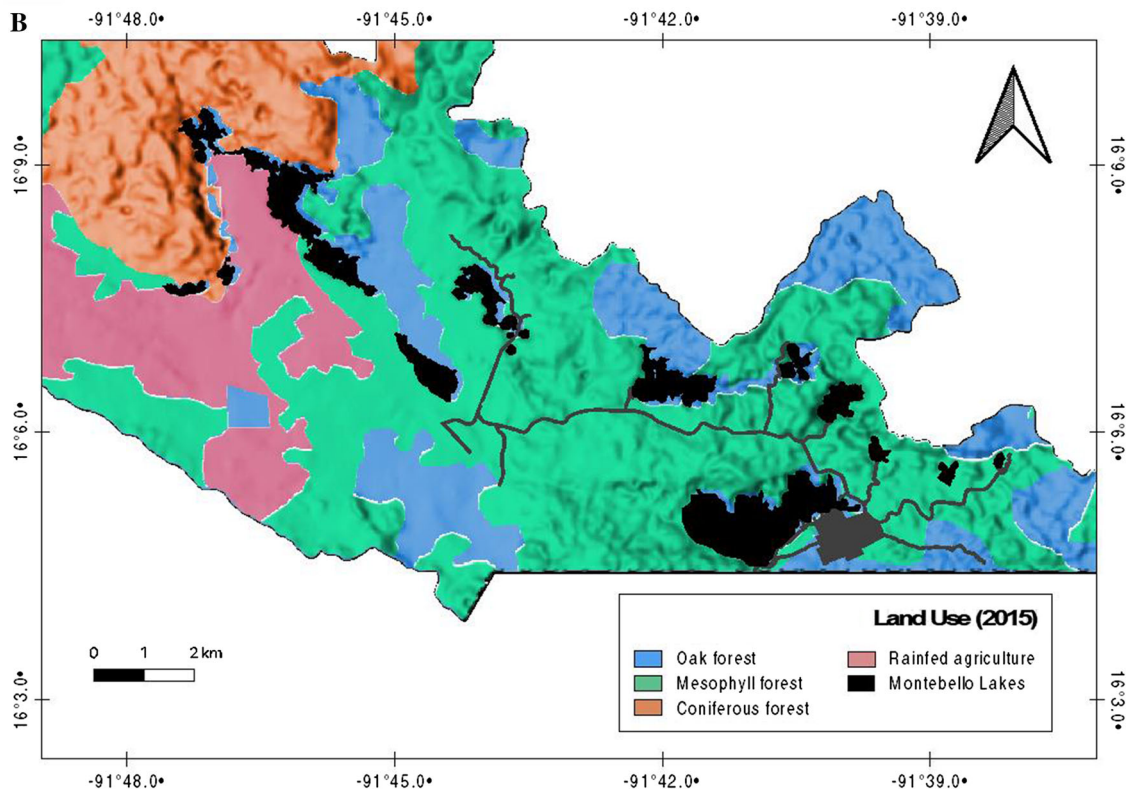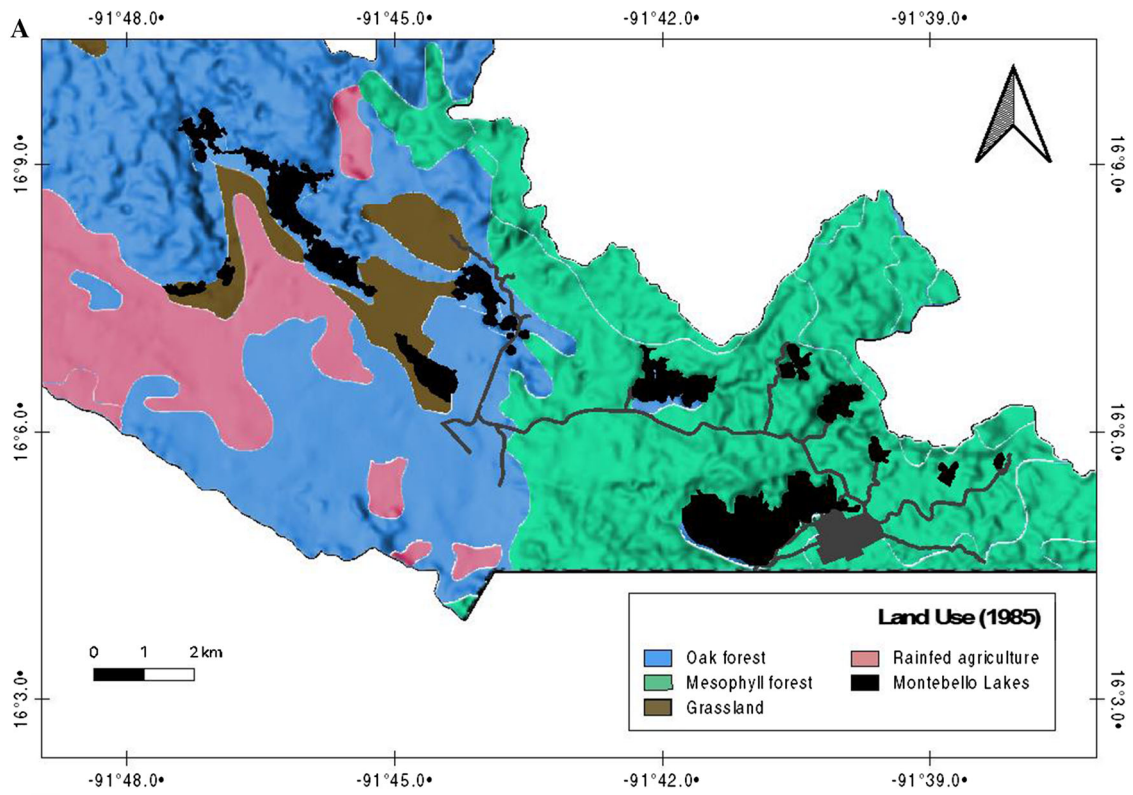
Large-scale human activities (agriculture, urbanization, wastewater pollution) have had greatest impact in the NW sector of the LMNP. Land-use change is an important factor at the basin and local scales (Fig. 9).

According to data from the 1994 National Forest Inventory, 61.39% of mesophilic forests in the LMNP

had been disturbed or fragmented, and 10% of temperate forests were in the same situation, leaving only 28.61% in a good state of conservation. An analysis of the deforestation of the LMNP (March Mitsuf and Flamenco Sandoval 1996) revealed 4752 ha of the vegetation (71.96% of the national park area) were well preserved in the 1970s, whereas by 1988–1993, the well-conserved area had declined to 264 ha (4% of the national park area).

Crops grown in the region are diverse, but are centered on tomato, cultivated throughout the year in greenhouses using fertilizer, and on maize and beans, which are cultivated only in the rainy season and supported by fertilizer additions throughout the year (Olea-Olea and Escolero 2018). Agriculture occupies 46.2–52.5% of the surface of the basin, testimony to the change in land use in recent years (López 2017; unpublished technical report of project CONAGUA-CONACYT 167603 2016), which favors loss of soils by erosion. Alvarado (2017) reported a loss of up to 89,421 tons ha^{-1} $year^{-1}$ in the study area. Since the 1980s, there has been an increase in agriculture in the center of the basin and urban expansion throughout the basin. Activities such as mechanized agriculture and expansion of vehicular transportation routes modified the natural dynamics of sediment transport in the basin (Cooper et al. 2013), which may, in part, explain the similarity of sediments between shallow and deep lakes.

Sediment carbonate content displayed a wide range within each lake type, making it impossible to use the

A

Land Use (1985)

- Oak forest
- Mesophyll forest
- Grassland
- Rainfed agriculture
- Montebello Lakes

0   1   2 km

B

Land Use (2015)

- Oak forest
- Mesophyll forest
- Coniferous forest
- Rainfed agriculture
- Montebello Lakes

0   1   2 km

measure to distinguish among them. The drainage basin is the ultimate carbonate source in this karst terrain. However, in addition to detrital carbonate inputs, biogenic carbonates, e.g. gastropod and ostracod shells, contribute to the carbonate content of sediments in some lakes. The carbonate content in sediments thus results from a combination of carbonates of lithogenic and biogenic origin. Calcite and dolomite saturation indices on the plateau lakes (1.43 ± 0.23 and 2.72 ± 0.47, respectively) were higher than in the mountain lakes (0.47 ± 0.31 and 0.99 ± 0.74, respectively), suggesting higher precipitation of authigenic carbonates in the plateau lakes. Further investigations will be required to identify the processes that account for the wide range of carbonate concentrations measured in the sediments of the lakes.

Percent Corg in sediments was significantly higher in mountain lakes than in sediments of plateau lakes. Larger carbon content in the sediments of pristine/oligotrophic lakes was unexpected, considering the greater productivity in impacted/eutrophic lakes, which should lead to higher organic deposition in the sediments (Fig. 10).

Three factors likely account for this counterintuitive finding: (1) microbial communities in pristine surface and ground waters are almost insignificant; thus, organic matter is degraded slowly and accumulates (Knapp and Bromley-Challoner 2003), (2) terrestrial organic matter that enters the lakes from the surrounding rainforest is typically recalcitrant (e.g. cellulose, hemicellulose, tannin, lignin, phenols), and thus is hardly degraded and accumulates, (3) accumulation of particulate organic carbon is linked to the absence of oxygen (Sobek et al. 2009). Degradation in the anoxic hypolimnion must be very slow, and thus organic matter accumulates in the sediments.

Contrary to expectations, we found no difference between percent Norg in sediments of pristine/oligotrophic and impacted/plateau lakes. Alcocer et al. (2018) found that total N concentrations in the water of shallow impacted/eutrophic Montebello lakes are 4.9–6.4 times higher than in waters of shallow pristine/oligotrophic ones. Even though eutrophication has led to an increase in N concentrations in the water column of the lakes, it has not caused a significant increase in the N content of the sediments. The high biomass of primary producers (up to 148.4 ± 14.1 µg Chl-a L^{-1}) in the shallow eutrophic lakes of Montebello (Alcocer et al. 2018) suggests very high primary production rates that incorporate large amounts of N in biomass, probably preventing its incorporation into the lake sediments. Moreover, decay of settled algal biomass in shallow eutrophic lakes consumes oxygen, favoring nitrogen loss from sediments via denitrification (Zhu et al. 2020). Lewis (2002) stressed the importance of nitrogen loss by denitrification in tropical lakes, associated with high temperatures, high microbial metabolic rates and prolonged periods of hypolimnetic hypoxia or anoxia.

Fig. 10 Biplots of mean particle size (Mz) versus organic carbon (Corg) in the Montebello lakes. (IE = impacted/eutrophic, PO = pristine/oligotrophic lakes)
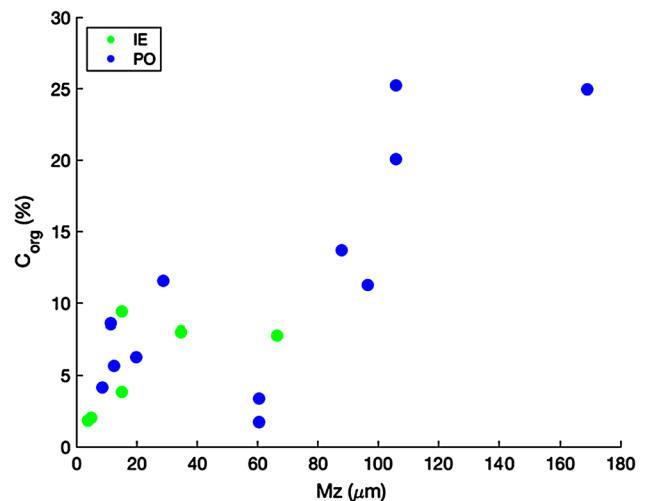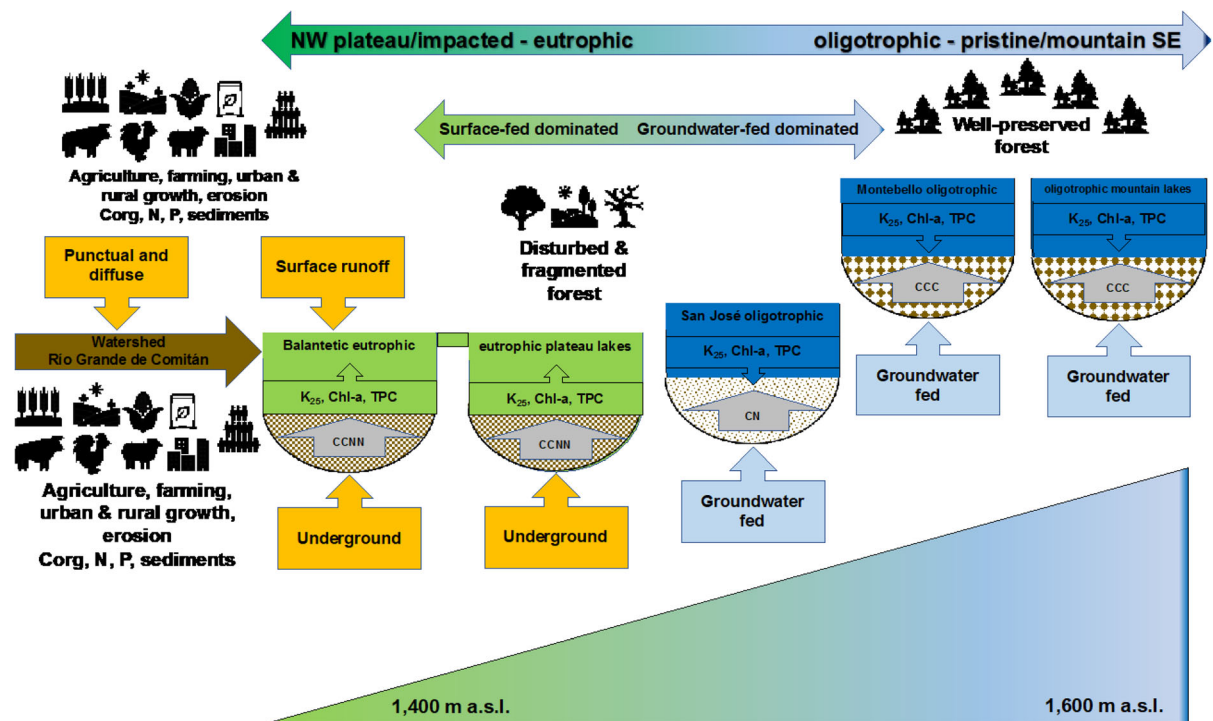
Fig. 11 Schematic representation of the two main agents explaining the differences of the sediments of the Montebello karstic lakes district: (1) location/topography (NW: plateau lakes to the left, lower altitude; SE: mountain lakes to the right, higher altitude) and (2) eutrophication (organic matter, agricultural drainage, deforestation). (Corg = organic carbon, N = nitrogen, P = phosphorus, K_{25} = electrical conductivity, Chl-a = chlorophyll "a" concentration, TPC = total particulate carbon). (Green = eutrophic, blue = oligotrophic). (Concentration increases: C $\rightarrow$ CC $\rightarrow$ CCC; N $\rightarrow$ NN). (Color figure online)

In temperate lakes, cultural eutrophication began in the 1940s and 1950s as a consequence of industrial growth, then spread and accelerated in the 1960s. By the late 1960s, water quality in many such lakes had deteriorated to a critical level (Farley 2012). The onset and trajectory of cultural eutrophication in tropical lakes is less well known. It seems to have accelerated around the 1970s, primarily associated with explosive increases in human populations and the expansion of agriculture. For example, in Lake Malawi, East Africa, nutrient enrichment appears to have begun around 1940; nonetheless, increased rates of sedimentation, phosphorus influx, and high abundances of eutrophic diatom taxa date to ca. 1980 (Otu et al. 2011). In the Neotropics, cultural eutrophication was documented in reservoirs in São Paolo, Brazil, beginning $\sim$ 1975, and accelerated in the 1980s and 1990s as a consequence of explosive growth of human populations in the drainage basins, and larger sewage loads (Costa-Böddeker et al. 2012; Fontana et al. 2014). In Lake

Petén Itzá, Guatemala, Rosenmeier et al. (2004) detected early human impacts (increased sediment accumulation) $\sim$ 1930, and evidence of strong eutrophication after 1965, coinciding with catchment population growth, watershed deforestation, and increased surface run-off.

In Mexico, where deforestation was a state-supported policy during the 1970s (PRONADE), a study of Lago Verde, on the coast of the Gulf of Mexico, shows a similar history, with early signs of human impact $\sim$ 1920 and an intense period of anthropogenic disturbance in the lake and its catchment between 1963 and 1990, with evidence of intense deforestation, erosion and lake eutrophication (Caballero et al. 2006; Lozano et al. 2007). The record from Lake Balantetic, one of the Montebello lakes, shows a long history of human disturbance dating back to the 1950s and intensifying in the 1990s, coinciding with rapid growth of the regional population, and evidence of deforestation, land erosion, and sewage discharge,

most likely through the Río Grande de Comitán (Caballero et al. 2019).

The timing of eutrophication of many tropical lakes fits well with that estimated for eutrophic Lake Balantetic, with early disturbances in the 1940s, but clear evidence of eutrophication from the 1980s onwards. The area has experienced expansion of human populations, enlargement of agricultural lands, increasing deforestation and land erosion, and greater sewage discharge, mostly carried by the Río Grande de Comitán (Caballero et al. 2019). Olea-Olea and Escolero (2018) concluded that leached nutrients, from intensive agriculture, contributed to eutrophication of the Montebello plateau lakes.

After topography, it seems that eutrophication is a secondary forcing agent affecting sediment characteristics, leading to coarser sediment grain size and higher Corg content. Small-scale agriculture and rural settlements have expanded towards the central and the SE portions of the LMNP. If these developments continue, eutrophication will overtake location and topography as the forcing agent modifying sediments in the Montebello Lakes.

Conclusions

Two forcing agents explain differences in sediments of the Montebello lakes, which lie in a single karst lake district (Fig. 11). They include: (1) location and topography of the basin, which is the first and foremost agent. Plateau lakes and primarily surface-water-fed lakes in the NW have finer sediments with low Corg content, whereas mountain and principally groundwater-fed lakes in the SE have coarse sediments enriched in Corg; (2) Eutrophication, caused by deforestation, organic matter input and agricultural drainage, is the second most important agent. Cultural eutrophication, caused by delivery to the lakes of nutrients and organic-matter-rich waters from the Río Grande de Comitán and surrounding agricultural lands and urban areas, is reflected in higher concentrations of Chl-a, TPC and K_{25} in most lakes on the NW plateau. In comparison, oligotrophic conditions (lower concentrations of Chl-a, TPC, and K_{25}) are present in the SE mountain lakes.

Differences between lakes in the NW (mostly impacted plateau lakes) and the SE (mostly pristine mountain lakes) were expected and identified as follows:

(a) Water quality differed between the mountain pristine/oligotrophic lakes and the plateau impacted/eutrophic lakes. Cultural eutrophication caused increases in K_{25}, and Chl-a, and TPC concentrations in the impacted plateau lakes.

(b) Sediments of the Montebello Lakes were composed primarily of silts. As expected, mountain, pristine/oligotrophic lakes displayed coarser sediments (sand > clay) in comparison to plateau, impacted/eutrophic lakes, which had finer sediments (sand < clay).

(c) Corg content differed between the plateau and mountain lakes. Contrary to our expectations, Corg was higher in sediments of pristine/mountain lakes than in sediments of impacted/plateau lakes. Pristine/mountain lakes receive recalcitrant organic matter from the surrounding rainforest, which accumulates because it is difficult to degrade, particularly under anoxic conditions, and because of the reduced microbial community in the pristine lake environments.

Location is the factor that most influences sediment characteristics in the two lake groups. Grain size, and percent sand and Corg are all higher in mountain lakes (groundwater-dominated) than in plateau lakes (surface water-dominated). Cultural eutrophication, however, has begun to shift the sediment characteristics toward coarser grain size and greater Corg content. Cultural eutrophication reduces the lakes to two principal categories based on sediment characteristics, i.e. impacted/eutrophic and pristine/oligotrophic.

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