1er Informe Técnico
Los Lagos del Nevado De Toluca, México:
Centinelas para la Detección y Análisis del Cambio Ambiental Global

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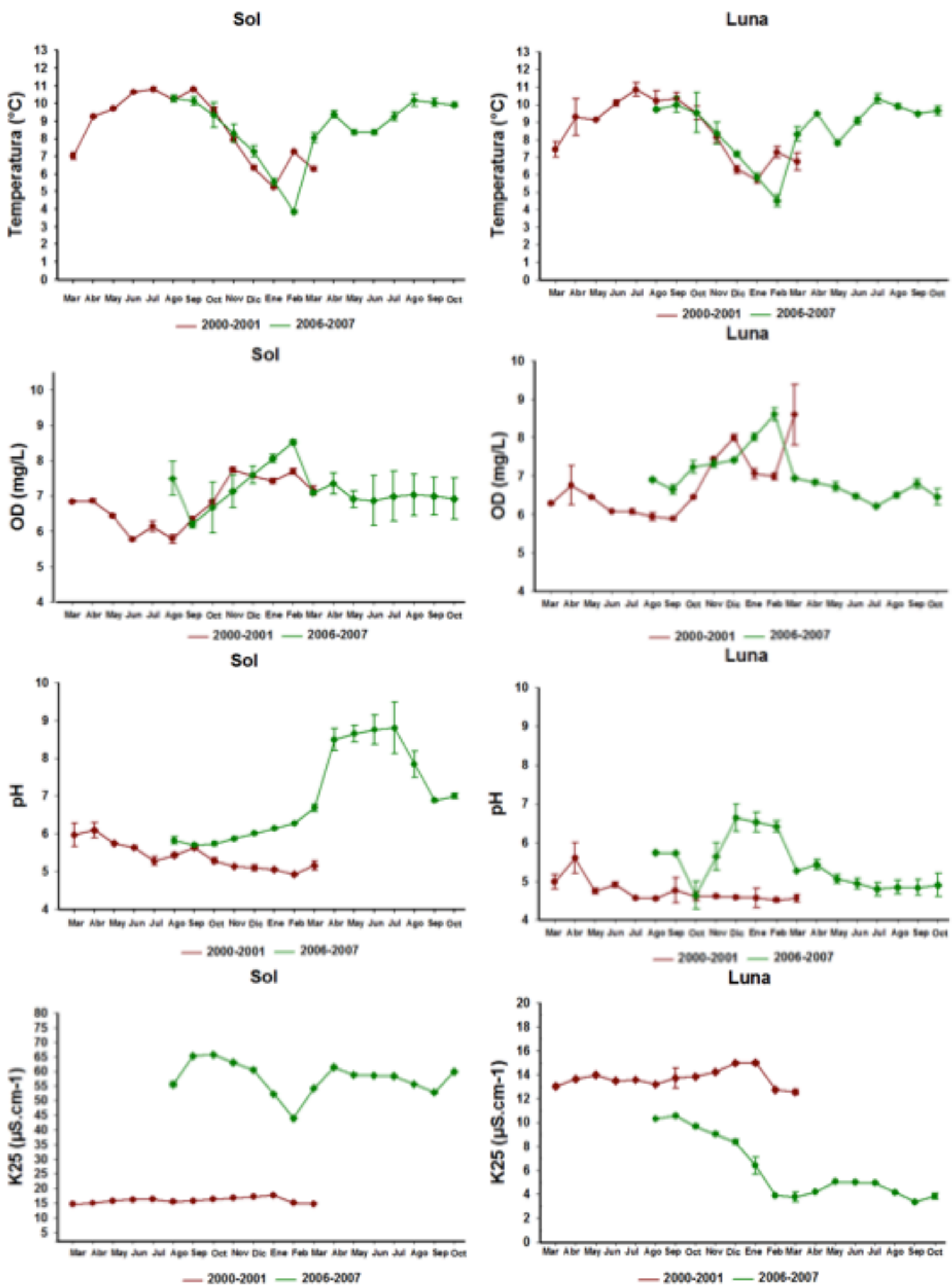
El presente proyecto apoyado por el PINCC tiene como objetivo general evaluar la potencialidad de los lagos de alta montaña ubicados en el cráter del volcán Nevado de Toluca como sitios de investigación (referencia/comparación) y para el estudio de Cambio Ambiental Global, así como el regional, constituyéndose en útiles "centinelas". Para cumplir con lo anterior se procedió a recopilar toda la información disponible sobre los lagos objeto de estudio y, una vez contando con la base de datos, se procedió a realizar una depuración y validación estadística de ésta para descartar aquellos registros atípicos ("outliers"). Existen diversos registros –la gran mayoría puntuales- de distintas fechas, de los cuales dos periodos temporales en particular son de gran utilidad por constituir series anuales continuas (marzo 2000 a marzo 2001 y Agosto 2006 a Octubre 2007), así como cubrir una conjunto de variables limnológicas relevantes.

Esta información constituye la tesis de Maestría en Ciencias del Mar y Limnología que está elaborando la Biól. Diana Ibarra Morales con el título de *Dinámica limnológica estacional e interanual de dos lagos tropicales de alta montaña: "El Sol" y "La Luna", Nevado de Toluca, México*. Esta tesis constituye el primero de los dos productos comprometidos (uno en el rubro de formación de recursos humanos y el otro en el rubro de publicaciones) en el proyecto. Asimismo, será la base para el sometimiento de un artículo de investigación a una revista arbitrada internacional.

A manera de ejemplo, a continuación se incluyen una serie de gráficos que muestran el comportamiento de algunas variables limnológicas que ilustran tanto la variación estacional (intra-anual) como la variación interanual.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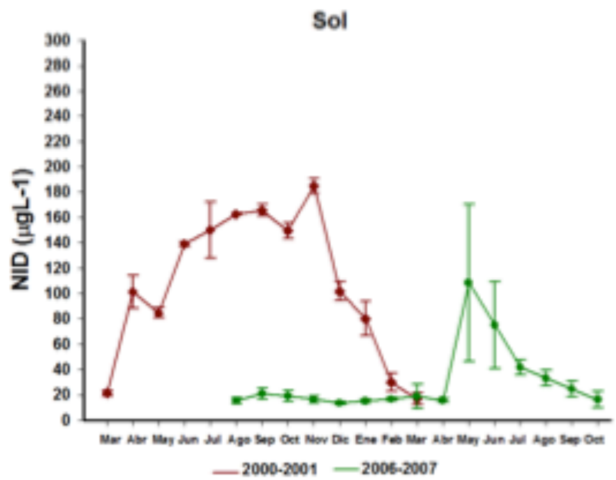
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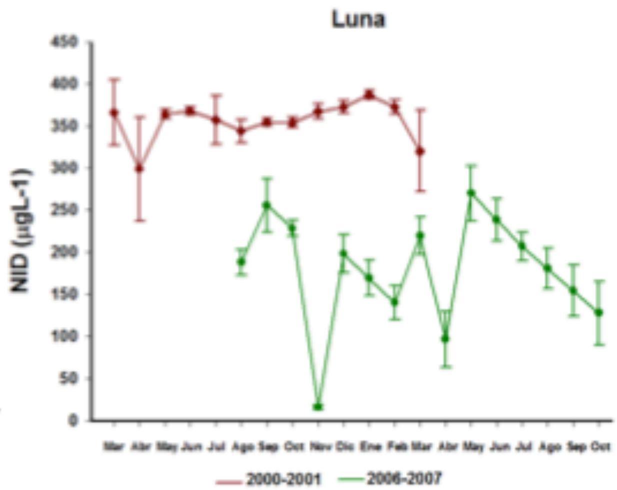
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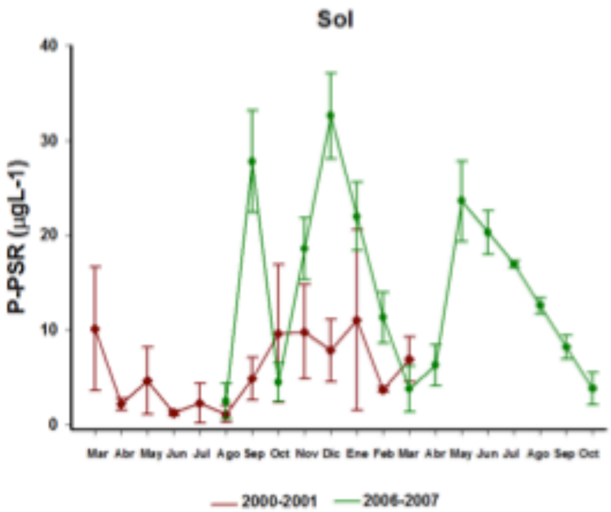
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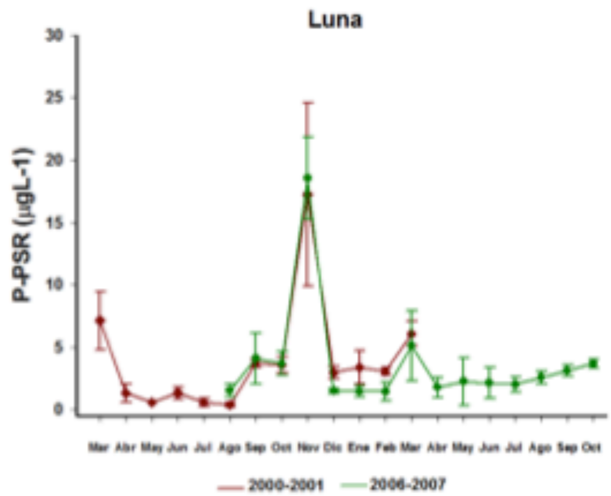
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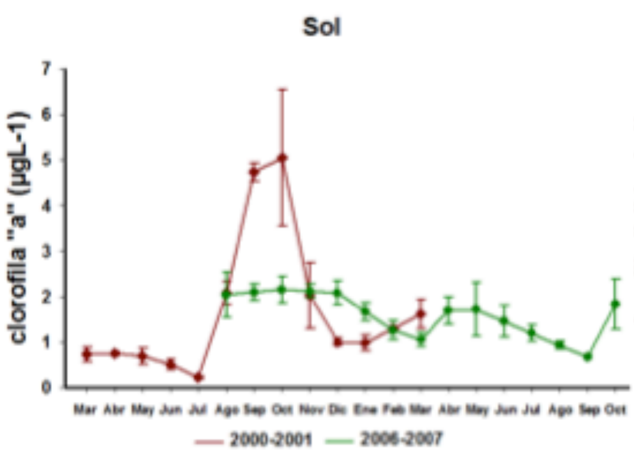
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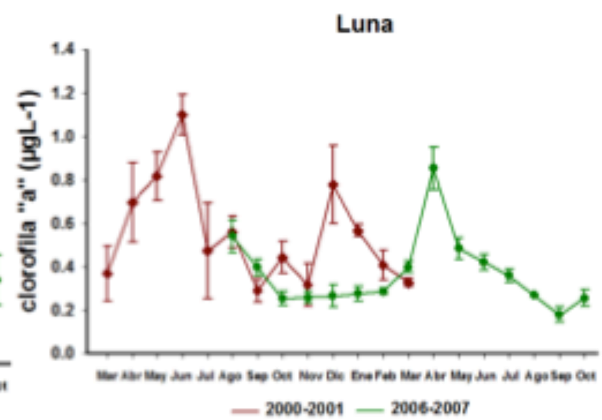
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2000-2001
2006-2007

Por otro lado, se cumplió con el segundo –y último- compromiso al publicarse el artículo *Environmental impacts of Little Ice Age cooling in central Mexico recorded in the sediments of a tropical alpine lake* por E. Cuna y otros en la revista *Journal of Paleolimnology* (Factor de Impacto 2012 = 2.209, indexada, internacional).

En este artículo se presenta evidencia de la "Little Ice Age" (la pequeña edad de hielo) en México con base en una secuencia sedimentaria con resolución decadal obtenida del lago La Luna, Nevado de Toluca. Se utilizaron una serie de proxies paleoclimáticos que mostraron que las condiciones actuales de este lago no han cambiado desde aprox. 1910, lo cual es evidencia de que no ha sufrido cambios derivados de la actividad humana.

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ORIGINAL PAPER

Environmental impacts of Little Ice Age cooling in central Mexico recorded in the sediments of a tropical alpine lake

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Abstract The Little Ice Age (LIA), AD 1350–1850, represents one of the most recent, persistent global climate oscillations. In Mexico, it has been associated with temperature decreases of 1.5–2 °C and mountain glacier advances, which are not accurately dated. We present new information about the nature of the LIA in central Mexico based on a decadal-resolution sediment sequence from high-altitude, tropical Lake La Luna, in the Nevado de Toluca volcano. We inferred past climatic and environmental changes using magnetic susceptibility, charcoal particles, palynomorphs, diatoms, cladoceran remains and multivariate statistics. The onset of the LIA corresponds with the beginning of a long-term trend to colder and drier climate ca. AD 1360–1910. The coolest and driest episode, ~AD 1660–1760, which corresponds with the Maunder Minimum in solar activity, was characterized by a cladoceran assemblage that showed the greatest dissimilarity to the modern one (no modern analogue), with the presence of cold-water species and *Daphnia* ephippia. The beginning of a warming trend ca. AD 1760, was identified by a diatom assemblage dominated by species with affinities for higher pH values (>6) and the greatest dissimilarity to the modern assemblage. This less cold, but still dry period, corresponds with historical reports of cattle and crop losses that predated the Mexican wars of Independence (AD 1810–1821) and Revolution (1910–1924). Modern conditions, established around AD 1910, resemble those during the Medieval Climate Anomaly (ca. AD 1200). No clear evidence of modern, human-induced environmental change was recorded,

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indicating that Lake La Luna is an ideal site in Mexico to monitor future impacts of global change.

Keywords LIA · Central Mexico · Tropical alpine lake · Diatoms · Cladocerans

Introduction

Lakes are excellent sensors of environmental change, and their sediments can provide high-resolution, decadal to sub-decadal records of climate fluctuations over long time-scales (Battarbee 2000). Studies of climate-driven processes in alpine lakes, which are located in sparsely vegetated catchments above tree-line, are less confounded than studies in lowland water bodies, because alpine lakes are not affected by complex soil and vegetation responses to human activities in their catchments. Those factors might otherwise influence external loading of carbon, nutrients, major ions and sediments (Catalan et al. 2002). Alpine lakes are particularly sensitive to climate change, and small differences in temperature between warm and cold periods can strongly affect the duration of ice or snow cover (Koining et al. 2002) and water level, thereby modifying lake water chemistry, the length of the growing period and the composition of aquatic plant and animal populations.

Late Holocene paleoclimate is characterized by a warm interval known as the Medieval Climate Anomaly (MCA), ~AD 1000–1300, which was followed by a highly variable, but generally cold period known as the Little Ice Age (LIA), ~AD 1350–1850 (Crowley and Lowery 2000; Mann et al. 2009). The LIA represents one of the most recent global climatic oscillations with abundant records in the North Atlantic region (Mann et al. 2009). Many authors have related cooling during the LIA with solar forcing, specifically with the lower solar irradiance during the Spörer (1450–1540) and Maunder (1645–1715) solar minima (Bond et al. 2001; Lozano-García et al. 2007). During the Maunder Minimum, solar activity and UV (200–300 nm) irradiance reached particularly low levels (Lean et al. 1995; Lean and Rind 1999). Although the LIA has also been associated with volcanic activity, lower solar irradiance was surely an important forcing during this cooling event (Crowley et al. 2008; Shindell et al. 2003). In Mexico, the LIA has been associated with temperature decreases between 1.5 and 2 °C (Lozano-García et al. 2007; Vázquez-Selem 2011) and mountain glacier advances of about 250 m (Vázquez-Selem 2011; Vázquez-Selem and Heine 2004). It has also been associated with high climate variability and recurrent drought events and epidemics between the fourteenth and nineteenth centuries (Contreras-Servin 2005; Florescano 1980; Metcalfe and Davies 2007; Therrel et al. 2004). The specific impact of the LIA cooling at each location, however, seems to depend on a delicate balance between a reduction in summer rainfall and an increase in winter rainfall, the latter a consequence of higher frequency and intensity of polar outbreaks ("nortes") (Jáuregui 1997; Lozano-García et al. 2007).

Even though historical records for central Mexico show that the LIA was a period of frequent droughts and epidemics, a more detailed interpretation of the pattern of climate change during this period can be difficult given that such records seldom cover the full interval of the LIA. Geomorphological evidence of glacial advances confirms the cooler conditions during the LIA in the central Mexico highlands, but they are difficult to date accurately (Vázquez-Selem and Heine 2004). Paleolimnological studies, on the other hand, can provide continuous records of environmental impact during the full span of the LIA, providing they have adequate chronologies and temporal resolution (multi- to sub-decadal), and that the climate signal is not masked by anthropogenic impact. The objectives of this work were to: (1) produce a high-resolution, continuous paleolimnological record from a relatively undisturbed site and (2) document the environmental effects of the LIA in central Mexico, specifically its onset, timing of maximum cooling and correlation with drought conditions.

Site description

Lakes La Luna and El Sol are shallow, permanent, alpine water bodies (19°06′N, 99°45′W, 4,200 m a.s.l.) located in the crater of the Nevado de Toluca volcano, central Mexico (Fig. 1). The lake catchments are characterized by andesic-dacitic boulders, sparse vegetation (alpine meadow) and cold climate. According to the 1970–2000 data from the closest meteorological station (4,110 m a.s.l., smn.conagua.gob.mx), mean annual temperature is 3.8 °C, ranging from an

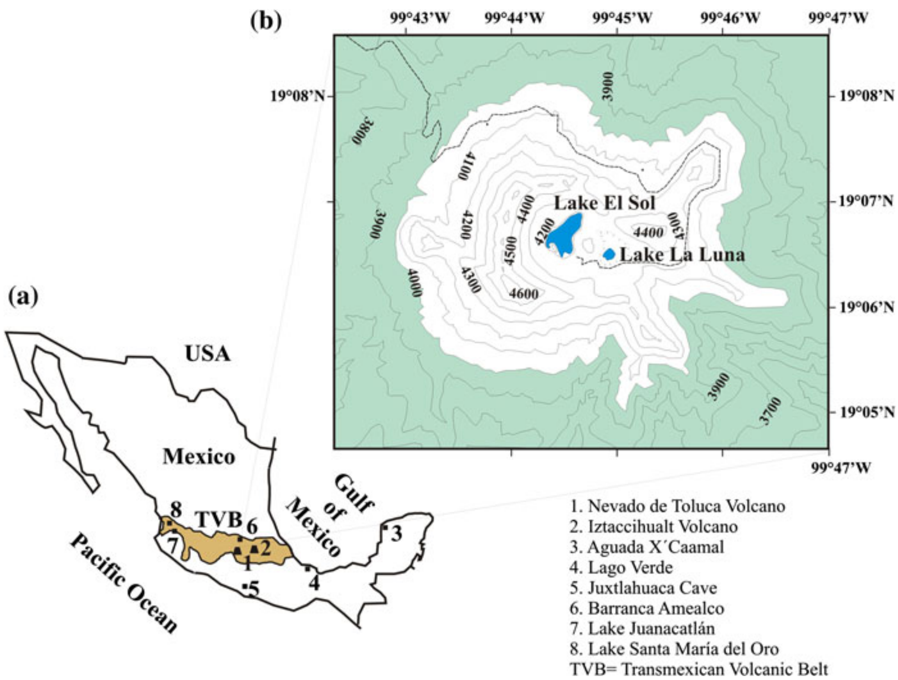

Fig. 1 Location of the study site **a** Location of Nevado de Toluca and other sites cited in the text; **b** Lakes El Sol and La Luna, in the crater of the Nevado de Toluca volcano, *shadowed area* represents arboreal vegetation cover

average of 2.4 °C during winter months to 5 °C during the warmest months (April–May). Extreme temperatures range from −9 °C in winter to 19 °C in spring. These lakes have positive water balance, with precipitation (1,213 mm/yr) concentrated during the summer months, exceeding evaporation (824 mm/yr). The waters of Lake La Luna, which originate from precipitation and snowmelt, have high transparency, low pH, low mineral content, and low alkalinity and buffering capacity (Table 1). Currently the lake has no fish. La Luna has been classified as an oligotrophic, warm polymictic lake (Alcocer et al. 2004). During very cold winters such as 2010, however, a thin ice layer can develop.

Materials and methods

A short sediment core (57 cm) was recovered in 2003 from the central part of Lake La Luna using a gravity corer. The core was sealed in a plastic tube and transported to the laboratory where it was cut in half lengthwise, photographed, described (sediment colour, texture, etc.) and sampled. Samples for diatom, chrysophyte cyst and cladoceran analyses were taken every 1 cm, whereas samples for palynomorphs and charcoal particle analysis were taken every 5 cm. Magnetic susceptibility measurements were carried out every 2 cm using a Bartington MS2C Core Sensor with a 10-cm internal diameter.

Excess ^{210}Pb ($^{210}Pb_{xs}$) in the top 14 cm was used for dating, with application of the CFCS (constant flux/constant sedimentation) model (Krishnaswami et al. 1971; Sánchez-Cabeza and Ruiz-Fernández 2012), which assumes constant atmospheric ^{210}Pb flux and constant sediment accumulation rate (SAR). A significant linear correlation between the logarithm of $^{210}Pb_{xs}$ activity and cumulative mass in the sediment core validated use of the CFCS model. The bottom sediment sample (56 cm) was sent to a commercial radiocarbon dating laboratory (Beta Analytic). Results from both dating methods were used to create the age/depth model (Fig. 2).

Additionally, surface sediment samples from the central, deepest area of the lake were collected in the summers of 2003 and 2010 using an Ekman dredge. Samples were removed from the top 2 cm of sediment and preserved with 4 % formaldehyde. Diatom, chrysophyte cyst and cladoceran analyses were also performed on these samples.

Table 1 Range of physicochemical characteristics and trophic state variables for lake La Luna during 2000–2001 (Alcocer et al. 2004) and 2010 (this work), showing mean values and standard deviations (N = number of months sampled, Z = water depth, DO = dissolved oxygen, K_{25} = electric conductivity at 25 °C, HCO_3^- = bicarbonate, Z_{SD} = Secchi disc transparency, $P\text{-}PO_4$ = orthophosphate, DIN = dissolved inorganic nitrogen $–N\text{-}NO_2 + N\text{-}NO_3 + N\text{-}NH_4–$, $Si\text{-}SiO_2$ = silicates)

Lake La Luna		
Period	2000–2001	2010
N	13	3
Physico-chemical characteristics		
Area (km^2)	0.02	–
Z max (m)	8.2 ± 0.4	9.3 ± 0.5
Temperature (°C)	8.6 ± 1.7	9.4 ± 2.3
DO (mg L^{-1})	6.8 ± 0.9	6.9 ± 0.9
K_{25} (µS cm^{-1})	14 ± 0.7	9 ± 0.1
pH	4.7 ± 0.3	6.2 ± 0.2
HCO_3^- (mg L^{-1})	–	3.9 ± 0.9
Trophic state variables		
Z_{SD} (m)	7.7 ± 1.5	8.3 ± 1.4
$P\text{-}PO_4$ (µg L^{-1})	4 ± 4	22 ± 26
DIN (µg L^{-1})	365 ± 24	153 ± 107
$Si\text{-}SiO_2$ (µg L^{-1})	17 ± 28	230 ± 212
Chlorophyll *a* (µg L^{-1})	< 1	< 1

Diatom samples were prepared by heating with 30 % H_2O_2 and 10 % HCl (Battarbee 1986). They were mounted on slides using Naphrax® and a minimum of 500 valves were counted per sample using a light microscope with inter-differential phase contrast (OLYMPUS BX50 1000x) to determine valve concentration (valves per gram dry sediment) and species relative abundance (%). Diatom taxonomy largely followed Krammer and Lange-Bertalot (1986). Teratological diatom valves were counted separately. Chrysophyte cysts were counted, but not identified, during diatom analysis.

Cladoceran samples were prepared following standard methods (Frey 1986). For every microscope slide, 0.1 ml of final solution was used. Identification was made at 100×, 200×, and 400× using an OLYMPUS BX50 light microscope. A minimum of 200 remains from each sample was counted. All cladoceran remains were counted (head shields, shells, postabdomens, postabdominal claws and ephippia). Claws and ephippia of the *Daphnia longispina* group were counted and graphed separately. The identification of cladoceran remains was based on Cervantes-Martinez et al. (2000), Elías-Gutiérrez et al. (2008), Frey (1986) and Sinev and Zawisza (2013). Preliminary cladoceran data were presented in Zawisza et al. (2012).

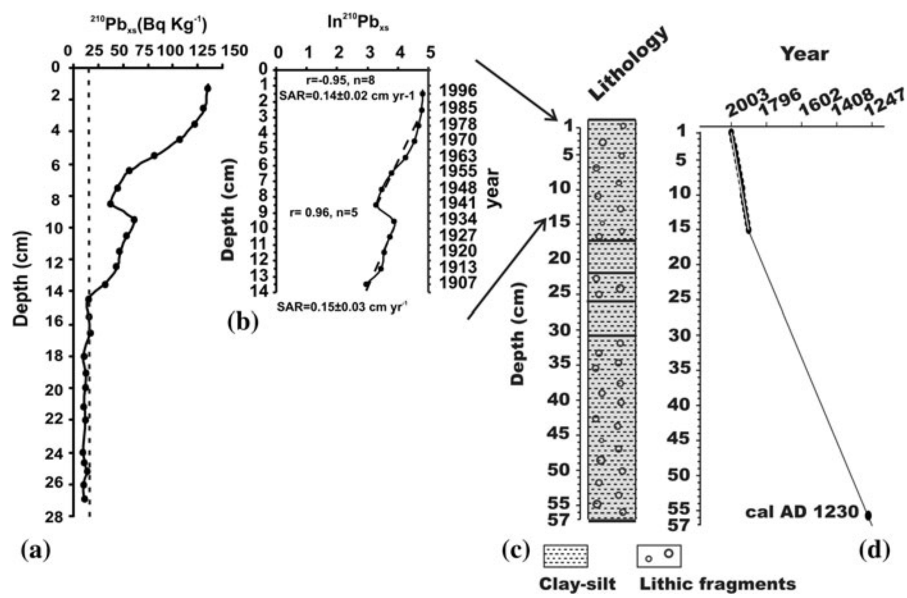

Fig. 2 **a** Total ^{210}Pb activity; the *dotted line* represents supported ^{210}Pb activity. **b** Logarithmic values of excess ^{210}Pb activity and ^{210}Pb-derived sediment accumulation rates. **c** Stratigraphic sequence and **d** age model for the 57-cm core from Lake La Luna

Samples for pollen analysis (1 cm^3) were prepared according to standard protocols (Faegri and Iversen 1989). Two *Lycopodium clavatum* tablets were added to each sample to allow calculation of pollen concentration (grains cm^{-3}) (Stockmarr 1972). Samples were analyzed at magnifications of 400× and 1,000×, using a transmission light microscope (Carl Zeiss Axiostar plus). Counts were made until a pollen sum of 500 grains was attained. Carbon particles (>100 µm) and palynomorphs were counted at the same time and in the same slides as pollen. The *Quercus*/*Pinus* (Q/P) ratio was calculated as an index of temperature change.

Diatoms, cladocerans, palynomorphs and pollen data are presented as relative abundances (%), whereas charcoal particles are presented as total concentration values (Fig. 2). Graphs were prepared using the program TGView 2.0.2 (Grimm 2004). To define diatom and cladoceran zones, stratigraphically constrained incremental sum-of-squares clustering was applied to the diatom and cladoceran percentage data using Edwards and Covali-Sforza′s chord distance, using the CONISS clustering subroutine in TILIA software (included in program TGView 2.0.2.).

Detrended correspondence analysis (DCA) was performed to evaluate diatom and cladoceran turnover through time and their association with environmental factors. Modern analogues were calculated as the dissimilarity (analogy degree) between all samples in the fossil record and the modern samples (2003 and 2010 surficial samples). The dissimilarity between samples was calculated using the scores of the DCA first four axes. These analyses were performed using diatom and cladoceran data (percentages) with the R Project (Team 2009) packages vegan (Oksanen et al. 2012) and paleoMAS (Correa-Metrio et al. 2012).

Results

The sediment sequence from Lake La Luna was homogenous in color and texture (silty-clay). Lithic fragments up to 2 mm diameter were present at most depths in the core except 31–26 cm and 22–17 cm (Fig. 2). Significant linear correlations (Student's test, $P < 0.05$) were found between ln $^{210}Pb_{ex}$ and cumulative mass in the sediment core, thus validating the use of the CFCS dating model. The ln $^{210}Pb_{ex}$ profiles obtained showed two regression lines, which indicated slight changes in linear sediment accumulation rates (SAR) with time (Sánchez-Cabeza and Ruiz-Fernández 2012): 0.14 ± 0.02 cm $year^{-1}$ (from surface to 9 cm depth) and 0.15 ± 0.03 cm $year^{-1}$ (from 9 to 14 cm depth). These sedimentation rates are, however, comparable within their uncertainties and a mean SAR of 0.14 ± 0.02 cm $year^{-1}$ was used to determine that the time elapsed since deposition of sediments at 14 cm depth was 97 ± 7 years. The conventional radiocarbon age for the bottom of the sequence (56 cm) was 800 ± 40 BP (Beta-195349), which after calibration (Calib 6, Reimer et al. 2004; Stuiver et al. 2005); gave an age of AD 1230 +20/−40, indicating that the record spans the entire LIA. The age model, using the ^{210}Pb and ^{14}C data, assumes a constant sedimentation rate of 0.06 cm $year^{-1}$ between 14 and 56 cm. Using this age model, the sampling interval of 1 cm provided an average temporal resolution of 7 years for the top 14 cm and 16 years for the rest of the core.

A total of 54 diatom species belonging to 24 genera were identified. The species composition was dominated (>10 %) by the benthic taxa *Cavinula pseudoscutiformis* (Hust.) D. G. Mann and Stickle, *Encyonema perpusillum* (Cleve-Euler) D. G. Mann, *Navicula* NTA, *Pinnularia microstauron* (Ehrenb.) Cleve, *Psammothidium helveticum* (Hust.) Bukht and Round and *P. levanderi* (Hust.) Bukht and Round. Dominance of benthic diatom taxa is related to the high transparency of water in the lake, which enables photosynthetic activity throughout the water column. Only one facultatively planktonic species was recorded, *Aulacoseira distans* (Ehren) Simonsen (Fig. 3). *Navicula* NTA is an unidentified species characteristic of modern Lake La Luna, which was reported previously by Caballero (1996). This species, as well as *E. perpusillum* and *P. helveticum*, were abundant in the modern samples from Lake La Luna, and show an affinity for the acidic (pH < 6) waters of this lake (Caballero 1996). *Cavinula pseudocutiformis* and *A. distans,* on the other hand, were rare in La Luna, but abundant in higher-pH (>6), neighboring Lake El Sol (Caballero 1996), indicating an affinity for slightly higher pH values. *Pinnularia microstauron,* currently not abundant in La Luna, is known to have a pH optimum of ~6 (Battarbee et al. 2011; Marchetto et al. 2009).

Five cladoceran species (*Alona manueli* Sinev and Zawisza, *Alonella pulchella* Herrick, *Chydorus* cf.

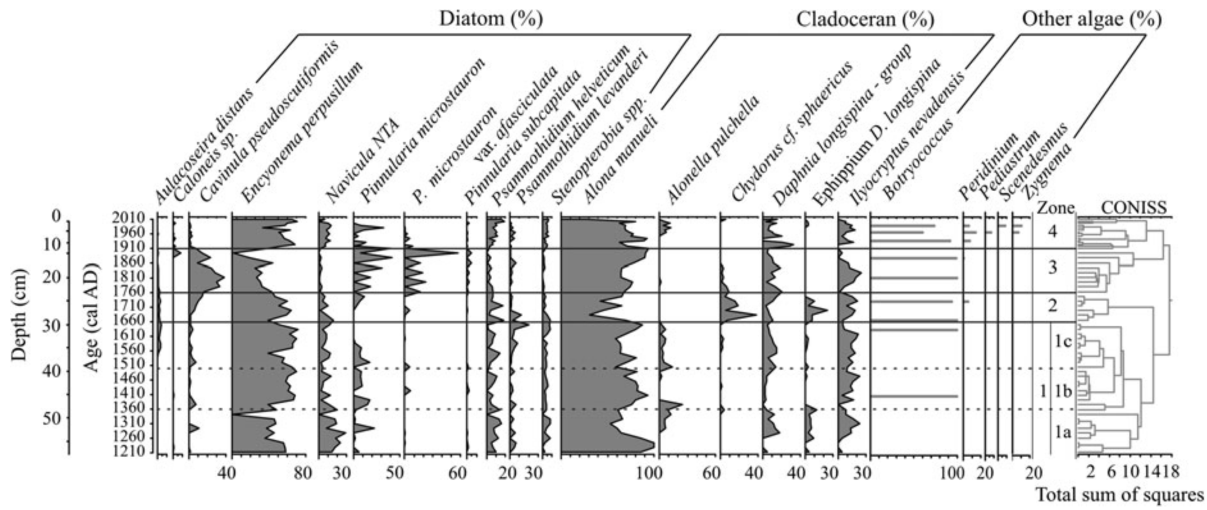

Fig. 3 Relative abundance (%) diagram for the most common diatoms (>2 %), cladoceran and chlorophyte taxa identified in the modern and core sediments from Lake La Luna, including the CONISS dendrogram on which zonation was based

sphaericus Müller, *Ilyocryptus nevadensis* Cervantes-Martínez, Gutiérrez-Aguirre and Elías-Gutiérrez and *Daphnia longispina* group Müller), belonging to three families (Chydoridae, Ilyocryptidae, Daphniidae), were recorded in the sediments from Lake La Luna (Fig. 3). The endemic littoral species, *A. manueli* and *I. nevadensis,* together with the planktonic *D. longispina* group, were the dominant (>10 %) taxa in the modern lake; these species are tolerant of the low nutrient concentrations and low pH values that prevail in this lake today (Cervantes-Martinez et al. 2000; Sinev and Zawisza 2013; Zawisza et al. 2012). Our observations also confirmed the presence of another littoral species in modern Lake La Luna, *A. pulchella*. This is a species commonly found in the cold-water lakes of the northern United States and Canada (Bennike et al. 2004; Hann and Chengalath 1981). This is the first record of *A. pulchella* in Mexico, as well as the southernmost record for the species (Sinev and Zawisza 2013). *Chydorus* cf. *sphaericus* is very tolerant of unfavorable climate conditions, especially cold water and low trophic status (Bennike et al. 2004; Sarmaja-Korjonen 2004). It was also present in modern Lake La Luna, but in very low numbers.

Total cladoceran concentration, together with the presence of teratological forms of *Encyonema perpusilla,* total diatom valves and chrysophyte cyst concentrations are presented in Fig. 4. Teratological valves and resting structures such as chrysophyte cysts and *Daphnia longispina*-group ephippia, are considered environmental stress indicators. In the case of teratological valves, the stress can be related to high levels of UV radiation (Falasco et al. 2009), and in the case of chrysophyte cysts and *Daphnia* ephippia, it could be related with unfavourable climate conditions, such as longer and colder winters, and even winter ice cover (Frey 1986).

Among the palynomorphs, five microalgae genera (*Botryococcus*, *Scenedesmus*, *Peridinium*, *Pediastrum* and *Zygnema*), but no aquatic plant pollen were recorded. The chlorophytes, which are currently present in La Luna at very low abundances, are in general favoured by nutrient enrichment (Reynolds 1998).

Total pollen concentration ranged from 609,467 to 158,816 grains cm^{-3}, with the lowest value at 49 cm and highest at 10 cm, and 19 types identified. The pollen record was characterized by high percentages of *Pinus*, *Quercus* and *Abies.* The pollen of these arboreal taxa was transported from the nearby forests below the tree line, however only *Pinus hartwegii* reaches the higher altitudes near the tree line (about 3,500–4,000 m asl). *Quercus* has a preferred distribution in lower altitudes and temperate climates (<2,500 m asl, Villers and López 1995). Increases in *Quercus* relative to *Pinus* (Q/P index, Fig. 4) are therefore interpreted as an indication of more temperate conditions. Pollen of *Zea* and *Typha* were present above 34 cm (~ AD 1595). These taxa do not belong to the surrounding alpine grassland vegetation or the

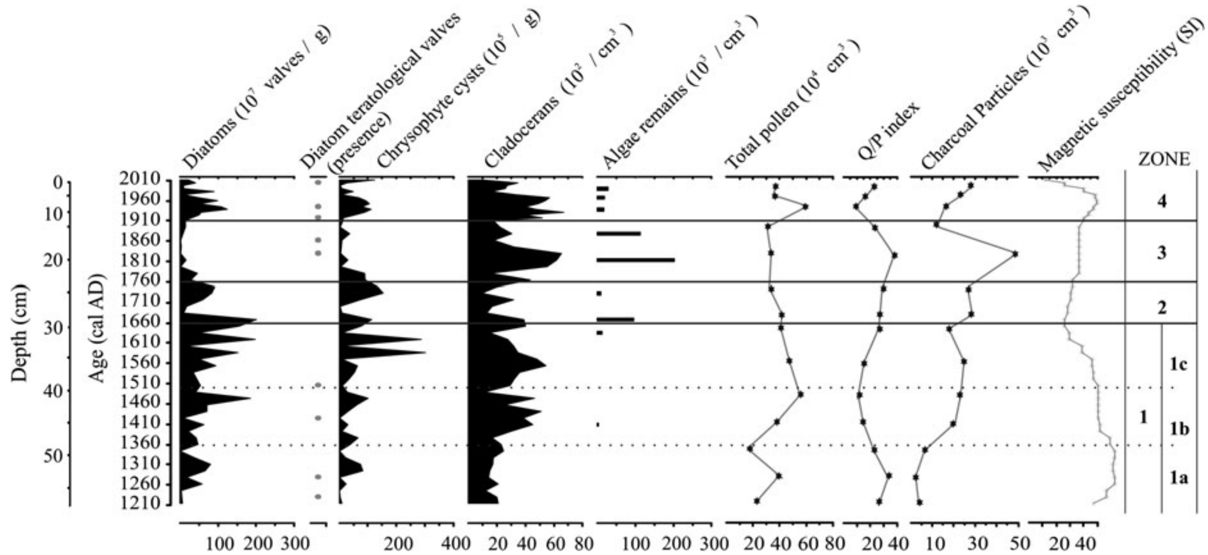

Fig. 4 Total concentration of diatom valves, presence of teratological valves, total concentration of chrysophyte cysts, cladoceran and chlorophyte remains, total pollen concentration, Q/P index values, charcoal particle concentration and magnetic susceptibility values, plotted against core depth and age

nearby forests. Their presence in the record from Lake La Luna can only be explained by aeolian long-distance transport, which is unlikely given the large size of these grains, or by human transport, which in this lake can be related with religious offerings during periods of prolonged drought, a practice that continues today (Quezada 1995).

Charcoal particles, transported to the lake from nearby fires, are taken as an indication of fire frequency (Clark 1988). Total charcoal concentration (Fig. 4) ranged between 2,286 and 49,789 particles cm^{-3} (lowest value at 53 cm and highest value at 20 cm). Magnetic susceptibility (MS) depends on the concentration of magnetic minerals in the sediment, transported from the catchment to the lake by surface runoff. In this simple catchment, MS can be directly correlated with precipitation. MS ranged between 12.8 and 45.8 SI, with the lowest values (<16 SI) between 32 and 28 cm and the highest values (>40 SI) between 54 and 47 cm (Fig. 4).

CONISS cluster analysis on diatom and cladoceran percentages identified four zones (Fig. 3), with Zone 1 further divided into 3 subzones: Zone 1 from 57 to 29 cm (subzones 1a 57–48, 1b 48–39 and 1c 39–29 cm), Zone 2 from 29 to 24 cm, Zone 3 from 24 to 14 cm and Zone 4 from 14 to 0 cm. According to the age model, these depths correspond with the following ages: Zone 1 from AD 1230 to 1660 (subzones 1a AD 1230–1360, 1b 1360–1500 and 1c 1500–1660), Zone 2 from 1660 to 1760, Zone 3 from 1760 to 1910 and Zone 4 from 1910 to 2003.

With respect to the DCA and the modern analogue analyses based on diatom assemblages (Fig. 5), DCA Axis 1 (eigenvalue 0.30, axis length 2.61) showed low sample scores (<0.5) in the oldest part of the core (Zone 1 and 2) and in the most recent samples (Zone 4). In these same intervals, the dissimilarity to modern diatom assemblages was lowest (<1), with a similar-to-modern diatom assemblage dominated by *Encyonema perpusillum, Navicula* NTA and *Psammothidium helveticum* (Figs. 3, 5). On the other hand, the highest DCA Axis 1 sample scores (>0.5) and the highest dissimilarity to modern diatom flora (>1) were recorded between depths 24 and 14 cm (Fig. 5). These depths, which correspond to Zone 3, have a non-modern-analogue diatom assemblage dominated by *Cavinula pseudoscutiformis*, *Pinnularia microstauron* and its variety *afasciculata*, and the lowest values of *Encyonema perpusillum*, *Navicula* NTA, *Psammothidium helveticum* and *Stenopterobia* spp. (Fig. 3). Given the ecological characteristics of these taxa (Battarbee et al. 2011; Caballero 1996), this assemblage is indicative of higher pH values (>6) and therefore this DCA Axis 1 is considered to show a pH gradient, with higher scores correlating with higher pH values.

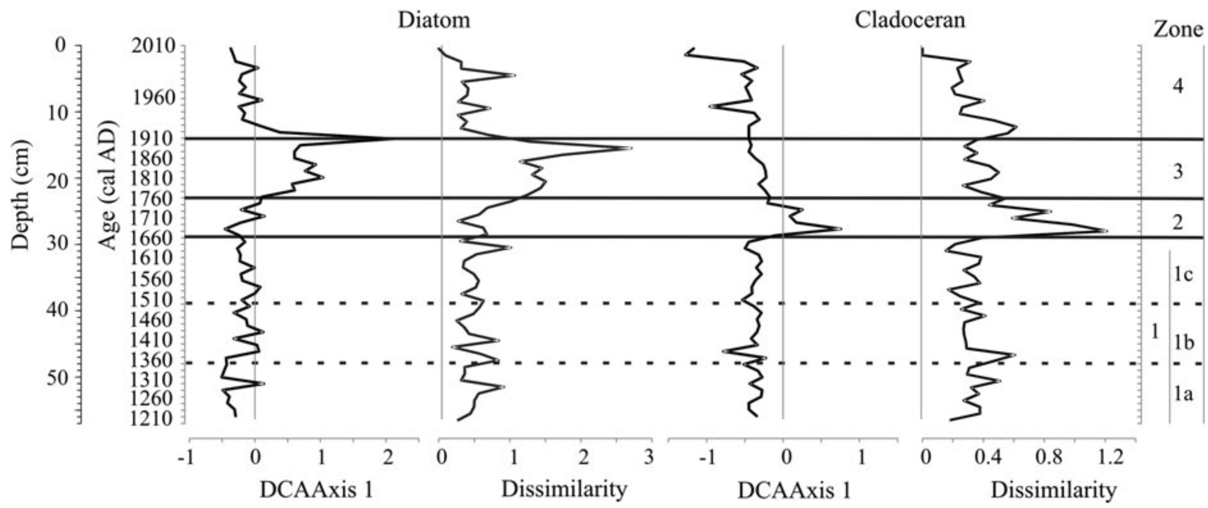

Fig. 5 DCA Axis 1 scores for samples following either their diatom and cladoceran assemblages (percentages) and modern analogue dissimilarity values for diatom and cladoceran assemblages (percentages) between surface sediment sample (2010) and core sediment samples

When the DCA and modern-single-analogue method were performed using the cladoceran assemblages, the DCA Axis 1 (eigenvalue 0.19, axis length 1.85) showed low sample scores (<0.2) in the oldest part of the core (Zone 1) and in the most recent samples (Zones 3 and 4). In these same intervals, the dissimilarity to modern fauna was lowest (<0.6). These zones have a similar-to-modern cladoceran assemblage, with *Alona manueli*, *Iliocryptus nevadensis* and the planktonic *Daphnia longispina* group. The highest DCA Axis 1 sample scores (>0.2) and the highest dissimilarity (> 0.6) to modern cladoceran fauna were recorded between depths of 31 and 25 cm (Fig. 5). These depths correspond to Zone 2, a zone that was characterized by abundance of cold-water-tolerant species *Chydorus* cf. *sphaericus* and *Daphnia longispina*-group ephippia, and by the lowest values of endemic littoral species *Alona manueli*. Given the ecological affinities of these species, this DCA Axis 1 is considered to represent temperature, with the highest scores correlating with lower temperatures.

Discussion

Lake evolution during the last 800 years

Zone 1 (∼AD 1230–1660)

Oldest sediments (∼AD 1230–1360; subzone 1a) represent the end of the MCA. The *E. perpusillum*-dominated assemblage of that time indicates low pH (pH < 6) and ultra-oligotrophic waters. Presence of teratological valves suggests environmental stress, which could be related with exposure to high ultraviolet radiation characteristic of high-altitude lakes with transparent water (Falasco et al. 2009). The low frequency of cladoceran remains and especially the occurrence of ephippia of the *D. longispina*–group, also support the idea of environmental stress (Bennike et al. 2004; Frey 1986). It is highly probable that during this time, low nutrient and pH conditions limited algal growth (Reynolds 1998), which explains the absence of other algal remains, and as a consequence, limited zooplankton development.

Low numbers of charcoal particles (low frequency of forest fires) and high magnetic susceptibility (high surface runoff and transport of terrestrial material to the lake), suggest relatively moist conditions. The high Q/P index is consistent with the inference for relatively warm conditions, correlating with the end of the MCA. Nevertheless, the load of nutrients and minerals entering the lake was seemingly low, reflecting the characteristics of the small catchment area (bare rocks, poor soil development, and limited vegetal cover).

Around AD 1360 (subzone 1b, ∼AD 1360–1500), lower magnetic susceptibility values, together with an increase in charcoal particles (lower runoff and higher forest fire frequency), suggest the beginning of a long-term (∼500-year) tendency to drier conditions that marks the transition between the MCA and the LIA. A shallower lake is supported by a decrease in planktonic cladocerans, which reached their lowest density (5 %) in the core. The lower Q/P index suggests slightly cooler conditions.

After AD 1500 (subzone 1c, ~AD 1500–1660), an increase in *Aulacoseira distans* is recorded. This facultatively planktonic species has been associated with particularly cold winters (Wolfe and Härtling 1996). Slightly lower temperature is also indicated in the subfossil cladoceran assemblages, mostly by an increase in *Alonella pulchella*. A decrease in pH is inferred from the lower values of *Pinnularia microstauron* (optimum pH ~ 6) at the top of the zone. The high abundance of chrysophyte cysts at the end of this period also indicates unfavorable or stressful conditions related to more acidic, shallower and cooler waters. The absence of teratological valves at the top of the zone could be related with a reduction in ultraviolet radiation that coincided with the beginning of the Maunder sunspot minimum (~AD 1645–1715). Lower magnetic susceptibility values and pollen concentrations, as well as an increase in charcoal particles, provide evidence for the continued tendency toward drier conditions. Pollen of *Zea* and *Typha* were recovered in this section of the sequence and, as discussed earlier, can be indicative of ceremonial offerings for rain.

Zone 2 (~AD 1660–1760)

The non-modern-analogue cladoceran assemblage, dominated by *Chydorus* cf. *sphaericus* and *Daphnia longispina* ephippia, is present in this zone, indicating the coldest conditions in the sequence, with seasonal or periodic environmental stress favoring the production of ephippia. In the diatom record, the presence of *A. distans* (Fig. 3) is also consistent with very cold conditions. The lowest magnetic susceptibility values in the core, together with the absence of lithic fragments in the sediment, a decrease in pollen concentration and an increase in charcoal particles, show a continuation of the long-term trend toward dry conditions. This zone therefore corresponds to the coldest and driest period in the record.

It is estimated that the altitude of the glacier equilibrium line in central Mexico (Iztaccihuatl volcano, Fig. 1) during the LIA was at 4,500 m asl, a 250-m depression (Vázquez-Selem 2011). Even though the Nevado de Toluca (4,558 m asl) was not high enough to develop true glaciers during the LIA, there is geomorphological evidence of the presence of rocky glaciers, but their exact age has not been established (Vázquez-Selem 2011; Vázquez-Selem and Heine 2004). It is possible that rocky glaciers were present in the Nevado de Toluca crater during this interval. Under this scenario, it is very likely that Lake La Luna (4,200 m a.s.l.) had a seasonal ice cover during this time, similar to the thin ice cover observed in March 2010, during a particularly cold winter. Cold conditions with periods of ice cover and very low nutrient levels could have limited diatom growth, as indicated by a decline in diatom abundance (Reynolds 1998). Absence of teratological valves extends to this period, which still corresponds to the Maunder minimum in solar activity (~AD 1645–1715).

Zone 3 (~AD 1760–1910)

During this period, the non-modern-analogue diatom assemblage was dominated by *Cavinula pseudoscutiformis* and *Pinnularia microstauron,* with the lowest values of acidophilic *Encyonema perpusillum*, *Psammothidium helveticum* and *Stenopterobia* spp. This assemblage is indicative of the highest pH values (>6) in the sequence. Cladocerans show a lower density of ephippia and of the cold-water-tolerant *Chydorus* cf. *sphaericus,* suggesting an increase in temperature. In high-altitude lakes, the regulation of acid–base equilibrium is more closely dictated by climate. In fact, temperature has been demonstrated to exert a first-order control on pH in several poorly buffered lakes in Alpine and Arctic regions (Koinig et al. 1998; Sommaruga-Wögrath et al. 1997). In those studies, warming trends were related to higher pH values and cooling was associated with lower pH values. In the record from Lake La Luna, a similar relationship between climate and pH is observed. The end of the LIA is marked by an increase in temperature, which is related to an increase in pH values.

This zone also shows the highest Q/P index values and charcoal particle concentrations in the core, also indicative of increasing temperatures and higher frequencies of forest fires in the region. An increase in lake nutrient levels is also suggested by the highest concentration of algae remains, especially *Botryococcus.* Higher productivity, together with sediment resuspension in a shallower lake, could lead to reduced water transparency, limiting the amount of light reaching the bottom of the lake and explaining the very low diatom abundance in this part of the record.

Zone 4 (~AD 1910–2003)

During the last several decades, conditions in Lake La Luna have become similar to those that prevailed in Zone 1, nearly 500 years before. A significant decrease in algae remains and an increase in diatom numbers are interpreted as a return to higher water transparency. Reappearance of an *E. perpusillum*-dominated assemblage indicates a return to lower pH conditions (<6). Algae remains, however, are more abundant than in Zone 1, indicating higher nutrient levels.

During modern times, the higher Q/P index and charcoal particle numbers followed the temperature increase at the beginning of the twentieth century. This increasing temperature trend is associated with the presence of teratological valves, indicative of higher ultraviolet radiation.

The increase in magnetic susceptibility and pollen concentration suggests higher precipitation and higher water level. In the first part of the twentieth century, a reduction in algae remains and disappearance of planktonic cladocerans (*Daphnia longispina*-group) was observed. This is taken as evidence of fish predation and could be the consequence of failed introductions of rainbow trout in this lake during the 1940s or 1950s, when government policies promoted fish introductions in several water bodies in central Mexico.

Ecosystem responses and climatic variability

The Lake La Luna sequence is a decadal-resolution record that covers the last 800 years and provides a detailed sequence of events that document the climatic impact of the LIA in central Mexico. In the record from Lake La Luna, it is clear that environmental change had a different effect on each of the biological groups studied. Each group displayed a different timing with respect to maximum change that correlated with ecological thresholds relevant for that group. The transition between the MCA and the LIA is dated at ~AD 1360 (subzone 1b) and is recorded as the beginning of a long-term trend to cooler and drier conditions, with lower magnetic susceptibility and higher charcoal particle concentrations. Dry conditions persisted until ~AD 1910 (end of Zone 3). Chrysophytes were the first to respond to the cooling trend, perhaps a response to seasonal ice cover, with an increase in cysts at about ~AD 1600. At that time, diatoms showed a minor change in their assemblage, mostly expressed as an increase in *A. distans*. A major change in the cladoceran assemblage followed, at ~AD 1660, when the *Chydorus* cf. *sphaericus*-dominated assemblage was established, defining the coolest and driest episode during the LIA, between ~AD 1660 and 1760 (Zone 2). During that time, longer and colder winters probably favored the presence of rocky glaciers within the Nevado de Toluca crater (Vázquez-Selem 2011; Vázquez-Selem and Heine 2004) as well as a seasonal ice cover on Lake La Luna.

Diatoms did not seem to respond to this cooling. Rather, their main assemblage change occurred at the end of the LIA. At the transition between colder and warmer conditions, presence of the *Cavinula pseudoscutiformis*-dominated assemblage, along with the decrease in acidophilic species *Encyonema perpusillum*, *Psammothidium helveticum* and *Stenopterobia* spp., defines a period with highest pH values in the lake (pH > 6) between ~AD 1760 and 1910 (Zone 3). At that time, the cladocerans show a gradual change towards their previous (similar-to-modern) assemblage. Algae also reacted to this transition by reaching their highest abundances, providing evidence that nutrient levels and turbidity were also higher. This period at the end of the LIA cooling suggests that under a future global warming scenario, the pH of water in Lake La Luna can be expected to increase.

After ~AD 1910, a trend towards higher moisture marks the end of the non-modern-analogue situation in the diatom assemblage, with the establishment of modern conditions that are very similar to those during the MCA. The modern lake, however, seems to be slightly less oligotrophic than during the MCA, as it has higher chlorophyte populations today. Except for the temporary loss of planktonic cladocerans around ~AD 1940, which may reflect failed attempts to introduce fish, our data show little evidence for human impact on the lake.

Comparison with other climate records

The LIA has been identified in several palaeoclimate records as a period of colder, but variable climate conditions (Jones and Mann 2004; Mann et al. 2009). Historical records from Mexico have shown this climate variability as a series of drought events between the fourteenth and nineteenth centuries (Contreras-Servin 2005; Florescano 1980; Metcalfe and Davies 2007; Therrel et al. 2004). Here we focus on the continuous, well-dated paleoclimatic records that cover the full LIA period in Mesoamerica. These include the Ti records from Lakes Santa María del Oro and Juanacatlán in western Mexico (Sosa-Nájera et al. 2010; Metcalfe et al. 2010), the dendrochronological record from Barranca Amealco in central Mexico (Stahle et al. 2011), the stalagmite record from Juxtlahuaca Cave in southern Mexico (Lachniet et al. 2012), diatom and pollen data from Lago Verde, in east-central Mexico (Lozano-García et al. 2007) and the oxygen isotope data from a sediment core collected in Aguada X'Caamal, Yucatan, Mexico (Hodell et al. 2005) (Fig. 1). Except for Lago Verde, all these records are sensitive to precipitation rather than temperature and correspond to areas with a net hydrological deficit. Lago Verde is also sensitive to temperature and corresponds to one of the wettest regions in Mexico, with a positive hydrological balance.

In Lake La Luna we identified the onset of the LIA at AD 1360 as the beginning of a period of drier conditions that lasted until AD 1910. In most of the previously mentioned paleoclimate records from Mesoamerica, the MCA to LIA transition is also recorded as a change to drier conditions that is dated to between AD 1365 and 1400, with a second dry spell from 1650 to 1780 (Fig. 6). At Juxtlahuaca Cave, the drying trend is delayed and its onset is not recorded until ~ AD 1500. Only at Lago Verde is the beginning of the LIA (ca. AD 1350) recorded by an increasing trend in moisture. At this site, unlike the others, the analyzed climate proxies are sensitive to both temperature and moisture, and the record shows two deep-water phases that follow the Spörer and Maunder minima in solar activity (Lozano-García et al. 2007).

Dry tropical climatic conditions during the LIA have been explained by a more southerly position of the Intertropical Convergence Zone (ITCZ), inferred from low Ti concentrations between AD 1500 and 1800 in the marine Cariaco Basin record, north of Venezuela (Haugh et al. 2001, 2005), and by the prevalence of El Niño-like conditions (Lachniet et al. 2012; Mann et al. 2009). Both climate mechanisms

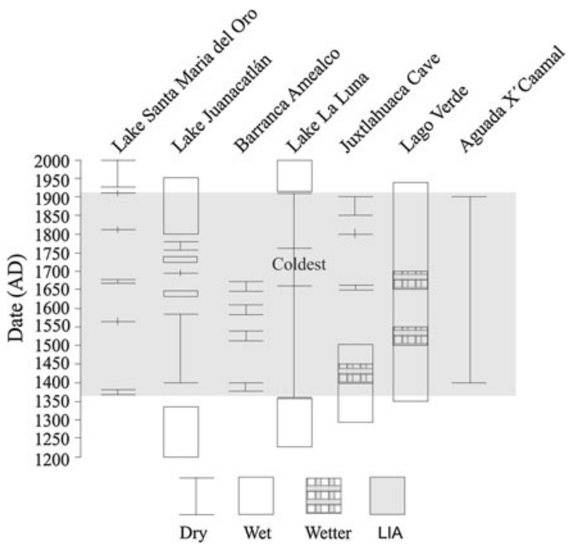

Fig. 6 Climate trends during the LIA identified in seven long, continuous, well-dated paleoenvironmental records from central Mexico. For site locations, see Fig. 1

reduce summer precipitation over most of Mexico, explaining the general agreement of most paleoclimate records with respect to dry conditions during the onset of the LIA. The record from Lago Verde (Fig. 1) (Lozano-García et al. 2007) indicates that this reduced summer precipitation signal will be evident as drought conditions, depending of course, on the local water balance, a factor that contributes to the different timing of drought recorded at each site. In the central Mexico highlands, where the water balance is usually negative, the drought signal is expected during the LIA, being more intense at sites with a higher water deficit. At Los Tuxtlas, where the water balance is positive, reduced summer precipitation was not sufficient to generate drought. On the contrary, the LIA is recorded as a wet period, given that more frequent polar outbreaks brought higher winter moisture and a more even distribution of precipitation throughout the year (Jáuregui 1997; Lozano-García et al. 2007). Lake La Luna, a high-altitude water body, has a moister climate than most other sites in central Mexico and currently has a slightly positive water balance. This allowed the relatively shallow lake (~ 10 m) to persist even during the coolest and driest episode of the LIA.

The role of more frequent polar outbreaks is an important climate factor to be considered, as it leads to colder and more humid winters, bringing the necessary moisture for the expansion of mountain glaciers on the

Transmexican Volcanic Belt, as documented by geomorphological evidence (Vázquez-Selem 2011), even under reduced summer precipitation. According to the La Luna record, cold winter conditions were established by AD 1600, with the coldest period between 1660 and 1760, an interval that broadly corresponds with the Maunder Minimum in solar activity, and which also correlates with the second of the two deep-water episodes at Lago Verde (Fig. 6). This interval is also consistent with the timing of the coldest northern hemisphere temperatures during the last millennium (Jones and Mann 2004; Matthews and Briffa 2005). We suggest that this period corresponds to the timing of the LIA glacier advances in central Mexico.

Within this climate context, drier than usual years during the LIA, recorded as famines and droughts in historical records (Endfield and O′Hara 1997), could correlate with years that had milder winters, less frequent polar outbreaks and lower winter moisture. This condition would lead, subsequently, to particularly dry springs. This climate scenario seems to explain the period between 1760 and 1910, at the end of the LIA, when less cold, but relatively dry conditions persisted at La Luna. The regional signal during this time seems to be less coherent among the long, continuous Mesoamerican records, but is shared by at least some of them such as Aguada X'Caamal (Fig. 6). This time correlates with the historical reports of low winter rainfall, shorter rainy seasons, and severe agricultural and cattle losses predating the Mexican wars of Independence (1810–1821) and Revolution (1910–1924) (Contreras-Servin 2005; Florescano 1980; Kienel et al. 2009; Swan 1981).

Lake La Luna is a sensitive ecosystem that responds rapidly to climate change. Biological assemblages that showed rapid changes during the LIA have remained relatively stable during the last few decades. These modern assemblages resemble those in the lake ~500 years ago, during the MCA, supporting the idea that MCA temperatures were similar to those recorded during the twentieth century (Crowley and Lowery 2000). This lake shows no clear evidence of modern, human-induced environmental change, which highlights the relevance of its frequent monitoring, as it can be considered a sentinel for future global change impacts in central Mexico.

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