Recent environmental changes in alpine Lake Kotlaničko as revealed by sedimentary diatom assemblages (Dinaric Alps, Bosnia and Herzegovina)

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Research Article

Keywords: Dinaric Alps, Paleolimnology, Diatoms, Environmental change, Bosnia and Herzegovina

Posted Date: April 1st, 2025

DOI: https://doi.org/10.21203/rs.3.rs-6234543/v1

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Journal of Paleolimnology on August 26th, 2025. See the published version at https://doi.org/10.1007/s10933-025-00372-0.

Abstract

Alpine regions are among the most sensitive ecosystems to climate warming, with alpine lakes being particularly affected by this forcing. However, none of these lakes in Bosnia and Herzegovina are regularly sampled or monitored, resulting in extremely scarce data and a largely unknown history of these lakes. We used a paleolimnological approach to identify and examine the main drivers of change in Lake Kotlaničko, located in the alpine tundra zone of the Zelengora Mountains in southeastern Bosnia and Herzegovina. We investigated changes in diatom assemblages using a 23 cm long sedimentary record and found a pronounced increase since the 1960s of planktonic diatoms (mainly *Lindavia radiosa*) relative to tychoplanktonic and benthic species. This change in diatom assemblage composition is likely associated with stronger thermal stratification due to longer ice-free seasons induced by rising regional air temperatures. In addition, the more recent period (since 2002) covered by the sedimentary record is marked by the occurrence of the planktonic *Asterionella formosa*, a taxon commonly found in mesotrophic to eutrophic lakes. The longer inferred periods of thermal stratification, combined with increased nutrients as revealed by the diatoms, suggest shifts in lake habitat and that Lake Kotlaničko has undergone important changes over the last ~ 65 years.

Introduction

Lakes serve as sentinels of environmental change, reflecting a broad spectrum of variables such as climate and catchment processes. They act as integrators of climate change, preserving evidence of past variations within their sediments (Lotter et al. 2010; Saulnier-Talbot 2016). Alpine lakes in Europe often embody the legacy of past glacial and periglacial processes, serving as distinctive and essential features of mountain landscapes (Oliva et al. 2019). These lakes hold significant potential for documenting environmental changes across various spatial and temporal scales, as they are highly sensitive indicators of ecosystem disturbances (Catalan & Rondón 2016; Pérez-Martínez et al. 2020; Preston et al. 2020). Recent anthropogenic influences have profoundly impacted alpine lakes worldwide, driving unequivocal changes in their functioning (Szabó et al. 2020). Among the most significant threats posed by climate change to these fragile ecosystems are biodiversity loss, declining water quality, and overall ecosystem degradation (Rogora et al. 2018).

Across Europe, high mountain ranges have experienced significant warming (Weckström et al. 2016; EEA 2017). In the Mediterranean region, alpine lakes are sensitive to global warming and related ecological changes because of a notable rise in air temperatures in high mountain regions (Gobiet et al. 2014). For example, since the end of the 19th century, the Alps have experienced warming at approximately two times the rate of the global mean, with the most striking warming since the 1980s (Kotlarski et al. 2023). A prominent increase in mean air temperatures since the 1960s in mountain areas of Bosnia and Herzegovina has been documented by several studies (Trbić et al. 2017; Popov et al. 2019; Gnjato et al. 2023). Due to this rapid warming, many mountain ranges have already experienced a reduction of snow cover duration, followed by glacier loss and extensive permafrost thawing (Huss et al. 2017; Obertegger & Flaim 2021). The biodiversity and productivity of mountain lakes have increased in response to climate warming (Råman Vinnå et al. 2021). Consequences are mainly manifested in altered snow and ice cover regimes, extended duration of growing seasons, enhanced thermal stability of water columns and alterations to nutrient cycles (Tingstad et al. 2011; Hofmann et al. 2020; Čelebičić et al. 2024). Moreover, shifts in precipitation patterns have impacts on lake water balances, particularly in watersheds with predominant limestone bedrock geology, which can cause significant water level variations from seasonal to multiannual scales (Hofmann et al. 2021).

The Zelengora Mountains, situated in the karst region of the Dinaric Alps in southeastern Bosnia and Herzegovina, rank among the country's most significant areas for biodiversity, cultural, and historical heritage (Gafić & Džeko 2008). A substantial part of the Zelengora Mountains is located within Sutjeska National Park, making the area a popular destination for outdoor activities such as hiking, sightseeing, and fishing. The Dinaric Alps, primarily composed of limestone, host a remarkable array of endemic plant and animal species. They also feature the highest concentration of alpine lakes in Bosnia and Herzegovina, including the notable Lake Kotlaničko (Fig. 1). The lake is regarded as one of Bosnia and Herzegovina's few remote lake ecosystems, offering valuable opportunities to study the effects of both natural and anthropogenic disturbances.

In high mountain lakes, microalgae such as diatoms (class Bacillariophyceae) are generally the main primary producers and, because of their abundance and rapid response to environmental change, they are often utilized in paleolimnological research (Lotter et al. 2010; Lin et al. 2018). Diatoms are unicellular algae with siliceous cell walls that live in aquatic habitats all over the world (Tetzner et al. 2022). They are particularly useful for studying environmental changes as they are well preserved in sedimentary records (Sienkiewicz et al. 2021). In the absence of past monitoring data, diatom sedimentary records in alpine environments often represent the only source of information on how lakes have responded to past environmental change and human activities (Larocque-Tobler 2017). Shifts in diatom assemblages may be associated with changes in water properties (e.g., nutrients, pH, light, temperature, oxygen level, salinity, and organic matter content), making them amongst the most frequently used bioindicators (Biskaborn et al. 2021). Diatoms are also excellent indicators of past climate change (Hundey et al. 2014; Moser et al. 2019; Michelutti et al. 2020), changes in atmospheric nitrogen deposition (Noble et al. 2020), and sulfur dioxide (SO_2) emissions (Heard et al. 2014).

The primary objectives of this study were: (1) to investigate environmental changes in Lake Kotlaničko and its catchment over recent decades, and (2) to identify the key drivers of these changes. The results of this study aim to anticipate the lake's response to the future changes and contribute to the development of appropriate management strategies for safeguarding aquatic ecosystems in this sensitive alpine region.

Materials and methods

Study site

Lake Kotlaničko (43°21’41” N; 18°29’02” E) is a lake situated in the alpine tundra zone at 1533 meters a.s.l. It is the deepest (9 m) and second largest (6.4 ha) lake in the Zelengora Mountains (Fig. 1). The mountain range is part of the Dinaric Alps region which contains eight lakes (alpine and subalpine), countless springs and streams, and several mountain summits that rise above 2000 m a.s.l. (Dekić et al. 2020). The lake was formed by deglacial processes and is located within a cirque (Cvijić 1900; Gafić & Džeko 2008); its catchment is composed of carbonaceous flysch and limestone bedrock (Cvijić 1924).

The Zelengora Mountains region experiences cold, wet winters and hot, dry summers, with the climate largely influenced by elevation and the proximity to the Adriatic Sea, which is the primary source of precipitation (Gnjato et al. 2022). The Čemerno meteorological station (located ~ 16 km southeast of the lake at 1304 m a.s.l.) registers an average annual air temperature and precipitation of 6.3°C and 1796 mm, respectively (Popov et al. 2019). Average winter (DJF) and summer (JJA) temperatures are − 2.1°C and 14.9°C, respectively, with an average precipitation of 523 mm in winter and 251 mm in summer. Ice covers the lake for roughly five months per year (November-March), usually melting in April (Gnjato et al. 2022).

Lake Kotlaničko is oligotrophic, with weakly alkaline water (pH 7.8) characterized by the calcium bicarbonate dominance and low specific conductivity (Gnjato et al. 2019). The lake is mainly replenished by underground karstic springs and seasonal precipitation, while several adjacent springs positioned along its western shoreline also supply the lake (Gnjato et al. 2022). On the lake's eastern shore, there is a surface outflow that drains underground approximately 100 m downstream of the lake’s outlet (Fig. 1b). The catchment flora is comprised of alpine tundra with alpine grasslands and shrubs. A substantial portion of the lake's bottom, along with the lake's shoreline, is covered with macrophytes. The lake fauna is represented by an endemic amphibian genus of newts (*Triturus*) and Arctic char (Gafić & Džeko 2008).

Field sampling and Core chronology

A 23 cm-long sediment core was extracted from the deepest point of Lake Kotlaničko in May 2019 from an inflatable boat using a Mini-Glew gravity corer (38 mm internal diameter). The core was sub-sampled *in situ* at 1 cm intervals after retrieval, sediments were placed into sterile Whirl-Pak bags, transported in a cooler and subsequently stored in the Laboratoire de Paléoécologie Aquatique (LPA) at 4°C until analysis. The core chronology was established by analyzing ^{210}Pb, ^{226}Ra and ^{137}Cs radioisotopes using gamma spectrometry (HPGe detector) in the Laboratoire de Radiochronologie of Centre d’études nordiques (CEN) at Université Laval (Quebec City, Canada) within the upper 17 cm. The age-depth relationship was calculated with the R package 'serac' based on ^{210}Pb activities and the constant rate of ^{210}Pb supply (CRS) dating model (Appleby 2001; Bruel & Sabatier 2020).

Loss-on-ignition and water content

The sediments were first freeze-dried to remove water, then heated in an oven for 24 h at 105°C to remove residual moisture before being placed in a desiccator. Samples were then weighed before combustion of organic matter in a muffle furnace at 550°C for 4 h, following Heiri et al. (2001). The percentage of organic matter in the sediment (% OM) was then determined by mass loss during the combustion process.

Diatoms

Microfossil samples were prepared for analysis following the method of Pienitz and Smol (1993). Sediment samples were freeze-dried for roughly 72 h to eliminate water and 50 mg dry weight of each sample was then placed in a glass vial and 10% hydrochloric acid (HCl) was added to eliminate carbonates. After allowing the reaction to complete, the supernatant was aspirated, and a 50:50 mixture of sulfuric (H_2SO_4) and nitric (HNO_3) acids was added, following which samples were heated to 60°C for two hours to oxidize organic matter. Samples were then aspirated and repeatedly rinsed with distilled water to eliminate any remaining acid. The siliceous slurries were mounted onto glass microscope slides using *Naphrax* mounting medium, and at least 300 diatom valves per sample were enumerated under oil immersion with a Zeiss Axioskop 2 light microscope equipped with differential interference contrast optics. Identification was carried out to the lowest taxonomic level attainable by applying established taxonomic guides (e.g., Krammer & Lange-Bertalot 1986, 1988, 1991a, b; Lange-Bertalot et al. 2017). The relative abundance of each reported taxon was computed as a percentage of the total number of diatoms enumerated and graphically presented using the software C2 (Juggins 2003). Diatom assemblage records were subjected to stratigraphically constrained cluster analysis (CONISS) with the package 'rioja' in the R environment (Juggins 2017), with significant diatom zones being determined by a broken-stick model, and the 'vegan' package (Oksanen et al. 2020) was used to compute the Shannon diversity index. The planktonic/benthic ratio (P/B) and a diatom-based *Lindavia* to *Stephanodiscus* (L/S) index were also computed for each sample. Shifts in the P/B ratio are regarded as indicators of changes in the lake ecosystem, whereas the L:S index, which reflects variations in lake stratification, was calculated as the sum of all species belonging to each genus using the formula (*Lindavia* − *Stephanodiscus*)/(*Lindavia* + *Stephanodiscus*); (Streib et al. 2021).

Results

Age model

Overall, the total ^{210}Pb activity decreased with sediment depth. The CRS age-depth model indicated that the upper 10 cm of Lake Kotlaničko sediments represented approximately the last 65 years. The unsupported ^{210}Pb (P_{bex}) activity was highest in the surface 1 cm, measuring 1161 ± 73 mBq g^{-1} (Fig. 2). The earliest ^{137}Cs peak appeared in the 10–11 cm sample, corresponding to the 1963 nuclear weapons test peak, as corroborated by the ^{210}Pb age model. High subsequent ^{137}Cs concentrations suggest that the lake site was significantly impacted by fallout from the 1986 Chernobyl disaster, indicating that the contribution from nuclear weapons test fallout is about ten-fold less than that of Chernobyl. The ^{137}Cs peak from Chernobyl was measured at 3691 ± 40 mBq g^{-1} in the 4–5 cm sample, again consistent with the ^{210}Pb model which indicated an age of 1985 ± 3 for the 4–5 cm section. The elevated ^{137}Cs concentrations between 5 and 10 cm core depth are likely due to the downward migration of Chernobyl fallout, while the somewhat elevated, but decreasing, ^{137}Cs concentrations between 1 and 4 cm core depth may result from factors such as delayed external inputs from catchment erosion or the lake's internal processes, including sediment focusing. Extrapolating the rate of average sedimentation at the base of the model implies a bottom core age of 1866, although we acknowledge that this age is hypothetical and requires confirmation through further chronological analysis.

Water content and organic matter

The sediments from Lake Kotlaničko had water and OM contents of 77–94% and 8.1–34.0%, respectively (Fig. 3). In general, stratigraphic profiles of both variables followed similar patterns, with decreasing trends from 16 to 12 cm core depth (WC 75.4–63.6% and OM 12.3–8.1%) and an increasing trend from 11 cm to the core surface, with a particularly noticeable increase within the top 6 cm (WC 85.9–94.0% and OM 18.3–34.0%). Maximum percentage values occurred in the surface sediments (0–1 cm).

Diatom analysis

A total of 106 different species of diatoms from 43 genera were identified in the 23 samples examined, although only 18 species were present with relative abundances exceeding 2.5%. *Staurosirella neopinnata*, *Staurosira venter*, *Staurosira* cf. *construens*, and *Lindavia radiosa* were the diatom species most commonly enumerated throughout the core (Fig. 3). The prevalence of alkaliphilic diatom taxa, the general predominance of benthic species, and the sudden shifts in the ratios of benthic and planktonic diatom taxa were the most notable characteristics of the stratigraphic profile. Three significant diatom zones were identified by CONISS:

Diatom Zone 1 (DZ1; 22–9 cm; prior to 1967 CE) characterized the core's lowermost section and was defined by the predominance of the oligohalobous, tychoplanktonic taxa *Staurosirella neopinnata* and *Staurosira venter*, with abundances reaching 48.3% and 50.2%, respectively (Fig. 3). Other fragilarioid taxa, such as *Pseudostaurosira brevistriata* (0–10.2%) and *Staurosira* cf. *construens* (2.0–8.7%), were also present in notable abundances. In addition to the dominance of tychoplanktonic taxa, benthic taxa such as *Amphora pediculus* (0–2.0%), *Achnanthidium minutissimum* (0.6–6.6%), and *Encyonema minutum* (0.3–5.6%) had their highest relative abundances in this zone (Fig. 3). Some species, including *Odontidium mesodon* and *Nitzschia dealpina*, occurred only in DZ1 (Fig. 3). The P/B ratio increased from 0.1 to 0.6 through this zone, whereas the *Lindavia*/*Stephanodiscus* index generally showed high values throughout the zone. Both the minimum (1.1) and maximum (2.7) values of the Shannon diversity index were observed in DZ1 (mean value for the whole core = 2.1). From 17 cm upwards, Shannon diversity values in this zone were ≥ 2.1 (Fig. 3).

Diatom Zone 2 (DZ2; 9–4 cm;~ 1967 to 2002 CE) was associated with a rapid overall decrease in the proportion of benthic taxa as well as in the two dominant tychoplanktonic diatom species *Staurosirella* *neopinnata* and *Staurosira venter* (Fig. 3). In contrast, DZ2 was marked by the rapid increase of planktonic diatoms which represented > 45% of the assemblage in each sample. This zone's upper limit (5 cm depth) was marked by a striking increase of *Lindavia radiosa*, which represented 23.8% of all diatoms counted in the 5–6 cm section (Fig. 3). In DZ2, diatom assemblages shifted distinctly towards the dominance of two planktonic taxa and the complete disappearance of *Odontidium mesodon* and *Nitzschia dealpina* (Fig. 3). Major planktonic taxa included *Lindavia radiosa* (20.3–45.4%) and *Stephanodiscus parvus* (3.6–36.3%), whereas other important taxa included *Staurosirella neopinnata* (9.9–16.7%), *Staurosira venter* (2.0–17.0%), *Amphora pediculus* (3.8–11.8%) and *Staurosira* cf. *construens* (1.6–5.1%) (Fig. 3). This zone was also characterized by the first appearances of the planktonic taxa *Asterionella formosa* and *Lindavia bodanica.* The highest P/B ratio values (from 0.9 to 1.5) and the lowest L/S index values (from − 0.2 to 0.9) were found in DZ2 (Fig. 3).

Diatom Zone 3 (DZ3; 4–0 cm; ~ 2002 to 2019 CE): Planktonic diatoms in DZ3 remained the dominant forms in terms of composition, making up on average 53.9% of diatom assemblages (Fig. 3). *Lindavia radiosa* increased in relative abundance to 49.1% near the top of the zone. Moreover, the abundance of *Asterionella formosa* increased from the bottom to the top of DZ3 (1.0–3.4%), whilst the presence of *Stephanodiscus parvus* decreased upwards in DZ3 and it was not encountered in the uppermost sample (Fig. 3). On the other hand, relative abundances of the tychoplanktonic *Staurosirella neopinnata* (6.1–17.0%), *Staurosira venter* (0–4.3%) and *Staurosira* cf. *construens* (4.5–11.3%) continued to be substantial, along with *Pseudostaurosira brevistriata* (0.3–8%) and *Pseudostaurosira brevistriata* var. *papillosa* (0–4.3%) (Fig. 3). Other benthic taxa remained in low abundances in DZ3, with *Amphora pediculus* being the most abundant benthic taxon, averaging 2.5% (Fig. 3). The P/B ratio continued to have high values in the range of 0.9 to 1.4, whilst the L/S index increased to values > 0.8 (Fig. 3).

Discussion

The paleorecord inferred from the diatom assemblages of Lake Kotlaničko indicates cooler alpine conditions with extended lake ice cover prior to 1956, but also in the period up to 1967. This was followed by a more recent, moderate increase in nutrient inputs linked to anthropogenic activities in the catchment and prolonged thermal stratification of the lake. Due to significant uncertainties in the age model for samples below the 10 cm horizon, we emphasize our interpretations for the past 65 years of the sediment record.

Climate change in the Zelengora Mountains

Our results indicate that from the core base (~ 1866) until 1967 climatic conditions in the Zelengora Mountains were cooler than today. Lake conditions were those of a shallow oligotrophic lake, with cold, turbid waters and extensive ice cover, as suggested by the predominance of tychoplanktonic taxa, including *Staurosira venter*, *Staurosirella neopinnata*, and *Pseudostaurosira brevistriata*, which are often found in shallow, oligotrophic turbid waters with prolonged ice cover (Rühland et al. 2015; Sienkiewicz

2016; Gardoki et al. 2023). Low organic matter and water content suggest higher inputs of fine-grained inorganic/clastic sediments, contributing to lake water turbidity.

A manifestation of climate warming in many ice-covered lakes has been the recent rise of planktonic diatom species or the increasing complexity and species richness of benthic diatom taxa (Rühland et al. 2015). Alpine paleolimnological archives from different parts of the globe show that small-celled centric species have recently flourished due to improved thermal stability of the water column and modifications to the availability of nutrients and light (Rühland et al. 2015; Yan et al. 2018; Moser et al. 2019; Hofmann et al. 2020). This is consistent with our results, as *Lindavia radiosa* increased at the expense of species such as *Staurosirella neopinnata* and *Staurosira venter* (Fig. 3). Air temperatures during the 1961–2020 period significantly increased at a rate of 0.3°C per decade as shown by the Čemerno meteorological station data (Gnjato et al. 2023). This 1.8°C increase in regional temperature is greater than the global warming of 1.5°C since pre-industrial levels (IPCC 2021), and the increase was likely amplified at the higher altitudes of the Zelengora Mountains. As such, the diatom shifts that we observed appear likely to be related largely to climate warming in the second half of the twentieth century.

Today, Lake Kotlaničko is known to be ice-covered for five months during the winter period (November-March). Additionally, the presence of *Asterionella formosa* in the upper 3 cm of the core (from 2011 to 2019) serves as an indicator of higher epilimnetic temperatures and modest eutrophication (Saros et al. 2005; Pienitz et al. 2006; Noble et al. 2020). Generally, *A. formosa* is associated with increased nitrogen concentrations (Köster et al. 2005; Moser et al. 2010). Notably, after 2002, there was a gradual disappearance of *Stephanodiscus parvus* in the sediment record, which is typically linked to a decrease in phosphorus concentrations (Streib et al. 2021; Dilworth et al. 2023), suggesting a shift in nutrient loading. *A. formosa* is commonly found in deeper lakes with stratified waters (Edlund et al. 2022), and its increased abundance is often interpreted to be a consequence of heightened atmospheric nitrogen deposition (Spaulding et al. 2015; Vazquez-Loureiro et al. 2023). This taxon also tends to be more competitive under stable water column conditions (Vazquez-Loureiro et al. 2023).

The shallow waters of the lake are densely covered with aquatic macrophytes at present, and the increased presence of epiphytic diatoms, such as *Amphora pediculus* — which grows on plant material like algae or vascular plants — indicates enhanced aquatic vegetation growth early in the record (at 17 cm core depth). These newly available habitats, driven by macrophyte growth, likely contributed to a gradual increase in assemblage diversity. Additionally, the rise in organic matter (OM) and water content (WC) between 22 and 17 cm further supports the notion of elevated organic matter production and higher trophic levels during this period.

This study demonstrates that the observed effects of climate change in the Zelengora Mountains align with shifts in diatom assemblages and sediment properties, such as organic matter (OM) and water content (WC). The diatom paleorecords provide valuable context for the significant increases in mean air temperature across Bosnia and Herzegovina since the late 1980s (Trbić et al. 2017), extending the perspective back to the early 1960s. However, to gain a better understanding of how rising temperatures drive limnological changes, a broader assessment of temporal trends across multiple lakes in the Zelengora Mountains is necessary. Studying the effects of climate change on a regional scale is expected to uncover lake-specific responses and diverse trends, which will ultimately clarify the overall consistency of these alpine lake systems. Therefore, sampling additional alpine lakes in the region—at varying altitudes and with different characteristics— is essential for establishing larger-scale ecological patterns and trends.

Changes related to land use

Shifts in the diatom record reflect anthropogenic catchment disturbance and increased nutrient loading throughout the Lake Kotlaničko paleorecord due to changes in land use and occupancy. Before 1967, positive L/S index values suggest lower trophic status (Streib et al. 2021). The highest relative abundances of *Achnanthidium minutissimum* and *Amphora pediculus*, both associated with nutrient-poor conditions (Chen et al. 2016; Sienkiewicz 2016; Snell et al. 2019; Mackay et al. 2020), also occurred during this period. The rise in the relative abundance of *Stephanodiscus parvus* (up to 36.3%) between 1967 and 2002 is likely linked to increased anthropogenic disturbances in the lake's catchment area during the latter half of the 20th century. Higher abundances of this taxon are typically associated with elevated nutrient levels, characteristic of mesotrophic and eutrophic waters (Lucas et al. 2015; Nisbeth et al. 2019; Dilworth et al. 2023). The increased nutrient loading and organic matter content, and the lowest L/S index values, especially between years 1967 and 1985, correspond to the time of intense regional livestock herding. This practice was widespread across several adjacent countries such as Croatia, Montenegro, Serbia, and Albania, while archival evidence points to its appearance in this region in the 13th century (Hrabak 1981). Moreover, Matley (1968) claimed that mountain areas of Bosnia and Herzegovina were one of the last areas in Europe where livestock herding became established. According to Drecun (1954), the central parts of the Zelengora Mountains, including Lake Kotlaničko, have been areas for livestock herding since “ancient times” and the beginning of these activities cannot be determined with precision. Until World War II, these areas were primarily used by a smaller portion of the population from the southern part of Bosnia and Herzegovina, specifically from the Humine region (lower Herzegovina), and livestock herding intensified notably in the postwar period (Drecun 1954). At the same time, with the postwar onset of industrialization in the southeastern region of Bosnia and Herzegovina, a substantial portion of the population started leaving rural areas and moved to cities, processes that reached their peak in this area during the 1970s (Gnjato 1991). This resulted in a drastic reduction in livestock herding and may be associated with the decrease of taxa indicative of eutrophication, such as *Stephanodiscus parvus*, in the uppermost section of our diatom paleorecord.

Conclusion

We employed a paleolimnological approach to analyze lake sediments, detecting episodes that reveal two primary drivers of change in Lake Kotlaničko, thereby placing recent direct observations into a broader historical context. The lake responded sensitively to multiple stressors, including climate change and anthropogenic influences. Our findings indicate that the functioning and dynamics of Lake Kotlaničko over the past 65 years have been shaped by the combined effects of climate warming and land-use changes.

The results underscore the need for improved spatial coverage to fully understand the diverse responses of lakes to the long-term cumulative impacts of these stressors, as well as the overall trajectory of Zelengora Mountain lakes. Additionally, further studies isolating the effects of individual stressors are essential for quantifying the impacts of global warming, atmospheric nitrogen deposition, and other concurrent stressors on lake functioning and dynamics in the sensitive alpine regions of Bosnia and Herzegovina.

This research represents the first study of its kind conducted on a lake sediment core in Bosnia and Herzegovina, marking a critical starting point for future investigations of paleoecological changes in other alpine lakes across the country.

Declarations

Author Contribution

S.G - carried out the analyses, collected the data and drafted the manuscript. D.A - provided funding support, helped organize and write the manuscript, assisted with data analysis and interpretation.R.P. - helped organize and write the manuscript, assisted with data analysis and interpretation.B.N - conceptualized the project, found funding, organized and participated in fieldwork, helped organize and write the manuscript, assisted with data analysis and interpretation.M.A. - contributed to sample analysis, the age-depth model and editing.O.G. - participated in fieldwork, sample analysis and editing.All authors reviewed the manuscript.

Acknowledgment

This research was supported by the Sentinel North program of Université Laval, made possible, in part, thanks to funding from the Canada First Research Excellence Fund, as well as the Natural Sciences and Engineering Research Council of Canada (NSERC) and Fonds de recherche du Québec - Nature et Technologie (FRQNT).

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Figures

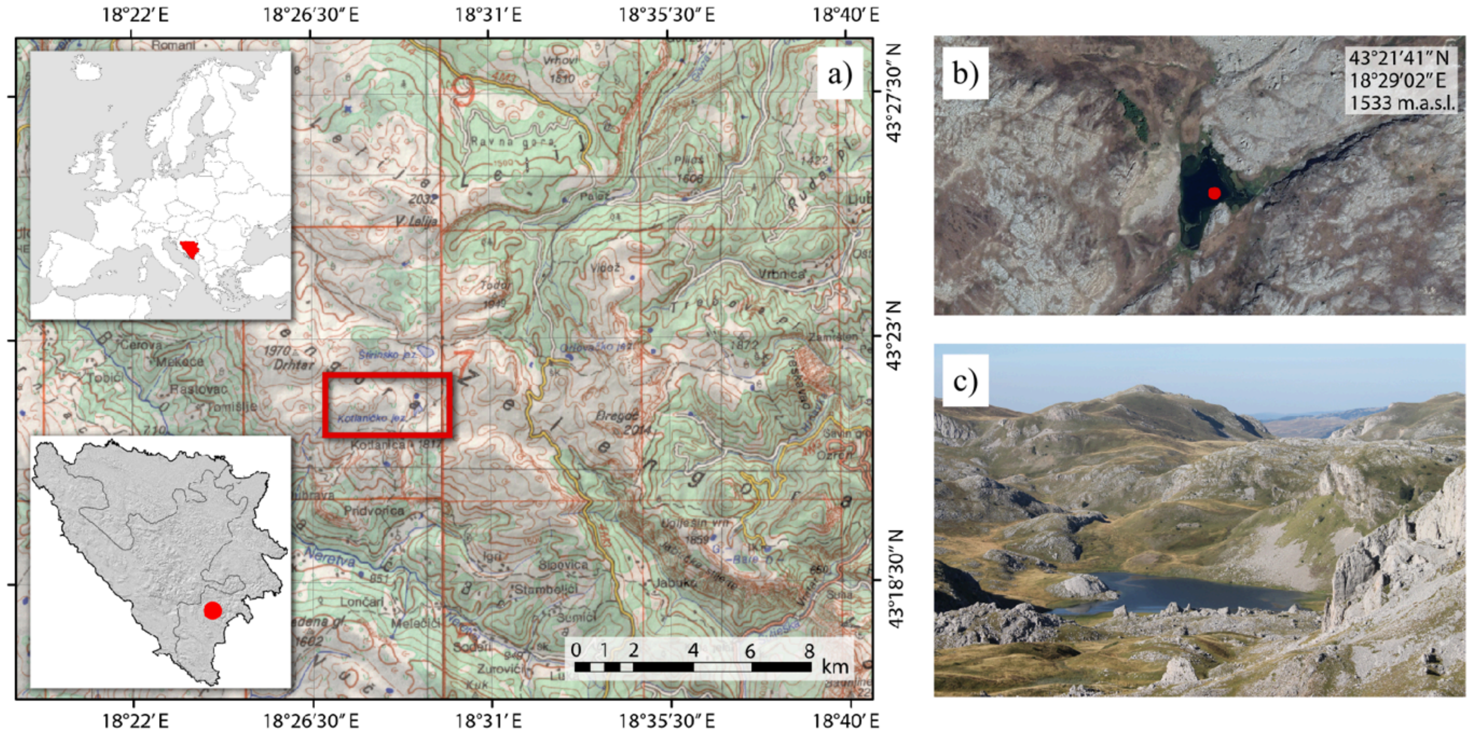

Figure 1

(a) Location of Lake Kotlaničko the Zelengora Mountains in Bosnia and Herzegovina in southeastern Europe; (b) satellite image of the lake and the coring location (red dot); and (c) a photograph of the lake in June 2016.

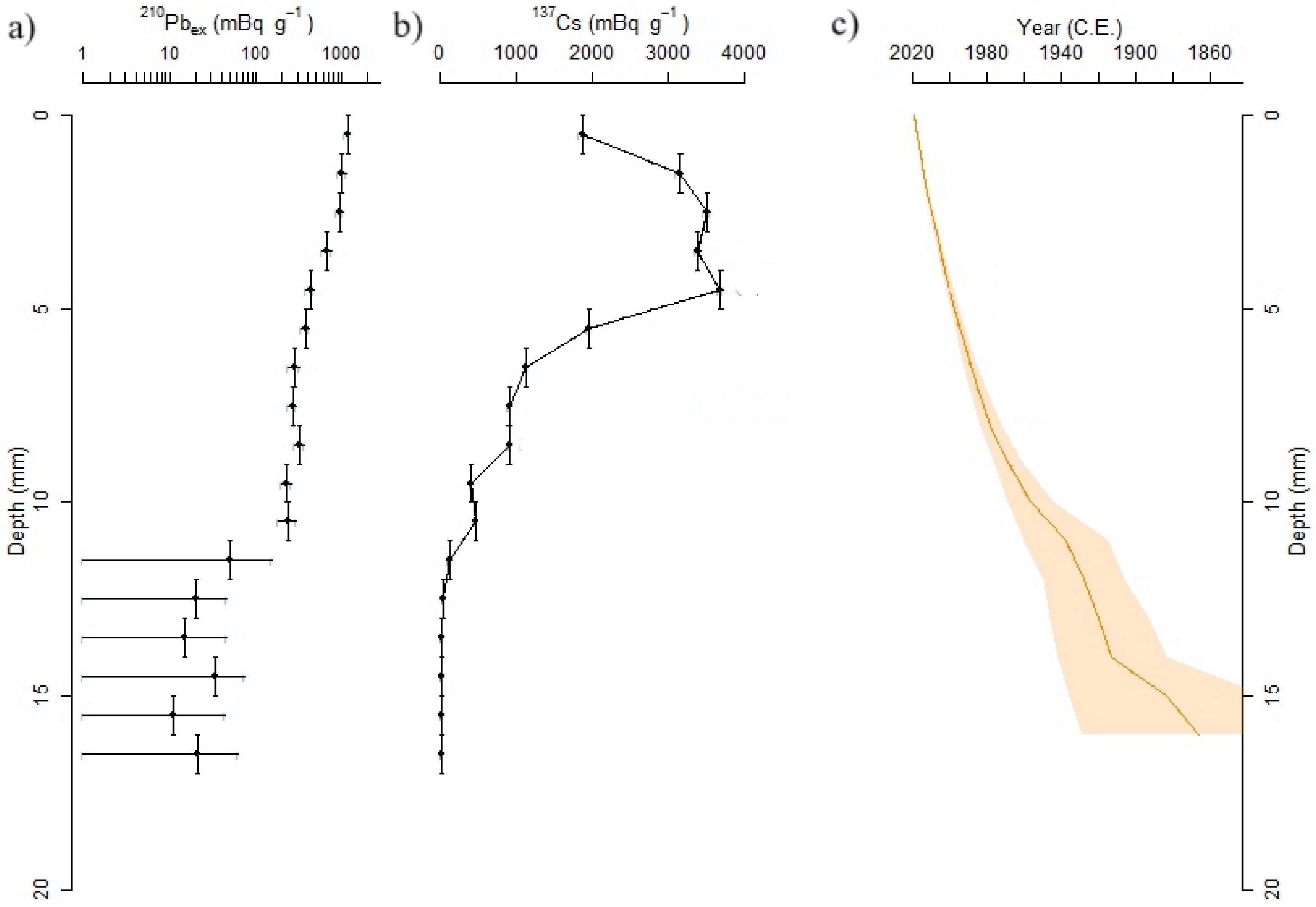

Figure 2

Radiometric chronology and age-depth model for the Lake Kotlaničko sediment core. a) variations in the radiometric activity of unsupported ^{210}Pb ($^{210}Pb_{ex}$) in sediment samples. Horizontal error bars show measurement errors; b) variations in ^{137}Cs activity in sediment samples; c) age-depth relationship based on the CRS model. The orange shaded region represents the 95% confidence limits of the age model. The dashed line shows the ^{137}Cs time marker matching the ^{210}Pb model.

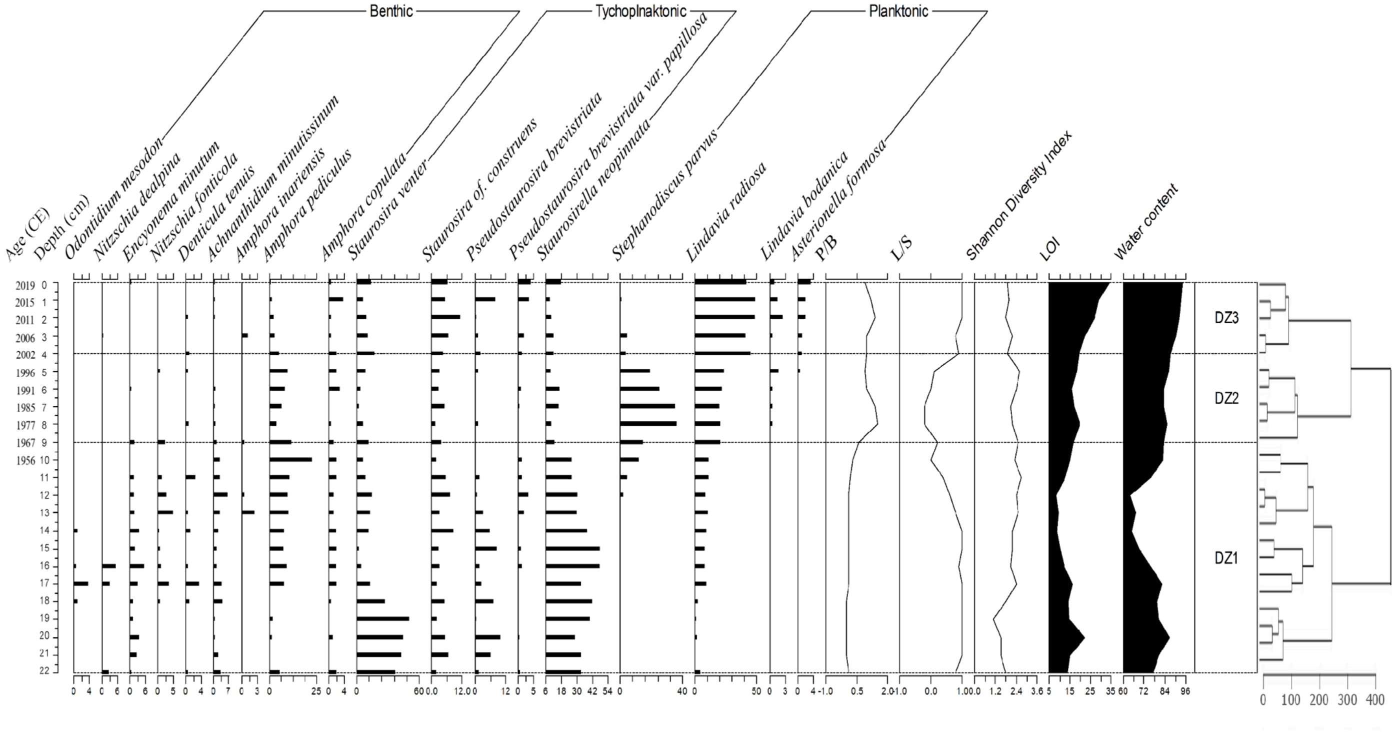

Figure 3

Stratigraphic diagram displaying shifts in the relative abundances (%) of selected diatom taxa (>2%) from Lake Kotlaničko, the P/B ratio (Planktic-to-Benthic ratio), the L/S index (*Lindavia*-to-*Stephanodiscus*index), the Shannon diversity index, Loss-on-ignition (LOI), Water content (WC), Diatom Zones (DZ) and CONISS dendrogram.