

## Postprint: Response of Diatoms in Jingpo Lake, Northeast China to Recent Climate Change and Human Disturbance

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### Abstract

Global warming and intensified human activities have led to functional degradation of numerous lake ecosystems across China, while current understanding of ecosystem changes in Northeast China lakes primarily derives from short-term monitoring. Taking Jingpo Lake in Northeast China as an example, this study analyzes the response processes of lake ecosystems, represented by diatom communities, to climate fluctuations and regional human activities over the past century through sedimentary records and modern monitoring data. The results indicate that before human disturbance intensified significantly, wind-driven disturbance was an important factor driving diatom community changes in Jingpo Lake, manifested as *Aulacoseira* species replacing small planktonic taxa (*Cyclostephanos*, *Stephanodiscus*, and *Discostella*) to become dominant. Since the 1970s, the successive increases in *Asterionella formosa*, *Nitzschia palea*, and *Fragilaria crotonensis* have reflected elevated lake nutrient levels resulting from intensified watershed agricultural activities, extensive application of agricultural fertilizers, and sewage discharge. Continuous temperature rise has already caused significant changes in diatom community structure in some lakes of Northeast China, yet the diatom record from Jingpo Lake shows no signal of this climate change. Considering differences in lake-watershed morphology and human activities, the study suggests that the impact of climate change on diatom community structure in Jingpo Lake over recent decades has been masked by strong human disturbance and thus has not manifested.

### Full Text

### Preamble

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## Diatom Response to Climate Change and Anthropogenic Disturbances in Jingpo Lake (NE China)

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### Abstract

Global warming and intensified human activities have led to the deterioration of lake environments and degradation of lake ecological services across China over the past few decades. In Northeast (NE) China, information about lake ecological changes in response to climate change and human activities has thus far derived mainly from short-term observations. In the present study, we selected Jingpo Lake in NE China as our study area. Using sediment records and paleolimnological methods, combined with long-term meteorological observations, we determined the patterns of diatom community responses to climate change and anthropogenic disturbances. The history of diatom assemblage changes over the past 130 years was reconstructed from Jingpo Lake sediments and compared with other diatom records from NE China to evaluate the impacts of climate change and human activities on diatom community shifts.

Our diatom records show a distinct shift from small-type planktonic species (e.g., *Stephanodiscus invisitatus*, *Stephanodiscus parvus*, *Discostella pseudostelligera*) to heavy-frustuled *Aulacoseira* species, implying that wind strength played an important role in diatom assemblage changes before the expansion of *Aulacoseira*. Successive increases in the abundance of *Asterionella formosa*, *Nitzschia palea*, and *Fragilaria crotonensis* since the end of the 1960s have reflected intensified agricultural activities, fertilizer usage, and sewage discharge, which have resulted in a trend toward eutrophication. While meteorological observations of the past 60 years reveal obvious climate warming in NE China, especially since the mid-1970s, and previous studies have shown that diatom communities in Xiaolongwan and Erlongwan (NE China) have clearly responded to climate warming, diatoms in Jingpo Lake have not responded in a similar way. Lakes Xiaolongwan and Erlongwan have similar climate conditions to Jingpo Lake but much smaller basins and catchments, and human activities in their catchments are much less intense. Therefore, it can be speculated that the impacts of climate warming on the diatom community shift in Jingpo Lake have been obscured by intense human disturbances. Additionally, intensified human activity has become the dominant factor leading to the ecological threshold being crossed in Jingpo Lake.

**Keywords:** Northeast China; diatom; climate change; human activity; Jingpo Lake

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## Introduction

Global change is exerting strong impacts on ecosystems, altering their inherent natural processes and increasingly threatening human living environments and socio-economic sustainable development [1]. As crucial freshwater resources, lakes have become one of Earth's most vulnerable ecosystems [2]. Over recent decades, as Northeast China has become an important national base for grain production and industry, lake water quality deterioration and ecological degradation have become increasingly severe [3]. Research on lake ecological changes in Northeast China has focused primarily on short-term or seasonal monitoring and analysis [4-8], with few long-term or decadal-scale studies, which limits deep understanding of lake ecological change processes and mechanisms. While limnological monitoring data can intuitively reflect ecosystem changes, most ecological monitoring records are short in duration, making paleolimnology a powerful tool for long-term lake ecological change research [9].

Among various ecological proxies, diatoms are one of the most commonly used indicators [10]. Diatoms are sensitive to environmental changes, widely distributed in various water bodies, and their siliceous frustules preserve well in sediments. Different diatom species have relatively clear environmental tolerances [9]. In subarctic and alpine regions, many lake sediment diatom records reflect climate warming since the Industrial Revolution, mainly characterized by increased abundance of small planktonic diatoms and corresponding decreases in large or non-planktonic species [11-14]. In mid-latitude regions, where human activities are relatively intensive and catchment surfaces and hydrological conditions have been artificially altered, lake ecosystems are subject to multiple environmental stressors simultaneously, making diatom community structure changes more complex [15-16].

How have diatom community structures changed in response to climate change and human activities in Northeast China? Do different watersheds show different diatom responses? What are the underlying causes? To address these scientific questions, this study uses Jingpo Lake as a case study to analyze diatom community structure changes and characteristics over the past century. We also compare Jingpo Lake's diatom records with those from maar lakes in the Longgang volcanic region (Xiaolongwan and Erlongwan), which are in the same climate zone but have substantially different watershed and lake characteristics, to distinguish the impacts of climate change and human activities on lake diatom assemblage changes and discuss their potential causes.

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## 1. Study Area

Jingpo Lake (43°46' -44°03' N, 128°37' -129°03' E) is located in Ning'an City, Heilongjiang Province. Formed during the Late Pleistocene to Holocene, the lake basin experienced a series of faulting and volcanic activities in its northern part. Erupted lava blocked the upper reaches of the Mudanjiang River, creating this large karst barrier lake [17]. The lake has a surface area of 91.5 km<sup>2</sup>, a catchment area of 11,820 km<sup>2</sup>, and an average depth of approximately 35 m. It is recharged mainly by surface runoff, with the Mudanjiang River providing the largest inflow.

The region has a temperate humid climate, with a multi-year average temperature of 4.1°C and multi-year average precipitation of 549 mm. Precipitation distribution varies significantly throughout the year, with rainfall concentrated in May-September accounting for approximately 85% of the annual total. Jingpo Lake's ice-covered period lasts from November through April of the following year [18]. Regional vegetation consists mainly of secondary deciduous-coniferous mixed forests that developed after logging, with forest coverage reaching 70%.

Surveys from the 1980s showed that phytoplankton were dominated by diatoms, particularly *Aulacoseira granulata* and *Asterionella formosa*. In the late 1980s, cyanobacteria (*Microcystis homogenea*) began forming blooms [17].

[Figure 1: see original paper] Location of Jingpo Lake and the coring site

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## 2. Methods

### 2.1 Sample Collection

In May 2012, a gravity corer (Austria) was used to collect a sediment core (JPS2) from the northeastern part of Jingpo Lake at a water depth of approximately 54 m. The retrieved samples were stored in PVC tubes and transported to the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, where they were kept at 4°C.

### 2.2 Chronology

The sediment chronology was established using <sup>21</sup>Pb and <sup>13</sup>Cs dating. All samples were freeze-dried and ground to pass through a 100-mesh sieve before analysis. Water content was analyzed and dry bulk density calculated for each sample. For <sup>21</sup>Pb dating, 0.5 g of dry sediment was used for non-destructive multi-nuclide measurement. Samples were placed in specialized test boxes and sealed for three weeks before measurement.

Analyses were performed using a high-purity germanium well-type detector (Ortec HPGc GWL), an Ortec919 spectrum controller, and an EG&G microcomputer-based multichannel analyzer system. Standard samples were



*pseudostelligera*. Facultative planktonic species were mainly *Aulacoseira granulata*, *Aulacoseira ambigua*, and *Discostella pseudostelligera*. Benthic or epiphytic species such as *Fragilaria* spp., *Navicula* spp., *Cymbella* spp., and *Achnanthes* spp. were also identified.

Based on cluster analysis, the JPS2 diatom stratigraphy can be divided into five zones:

**Zone Ia (40–32 cm, 1881–1947):** Dominated by planktonic species, with *C. dubius* as the most significant dominant species (relative percentage content 57.1%). The average percentage concentration range of *D. pseudostelligera* was 5.4%–57.1%. Other planktonic species such as *C. tholiformis* and facultative planktonic species *A. ambigua* also accounted for certain proportions. Benthic or epiphytic species *Nitzschia* spp. had relatively high proportions (4%–12%). The P/B (planktonic to benthic/epiphytic) ratio showed a slowly decreasing trend from bottom to top.

**Zone Ib (32–23 cm, 1947–1966):** Still dominated by *C. dubius* (average percentage content 21.5%), but with a slight decline. *A. ambigua* increased significantly (average relative percentage content about 28.5%). Other taxa showed little change compared to the previous stage. The P/B ratio decreased slightly.

**Zone IIa (23–14 cm, 1966–1986):** The diatom assemblage changed dramatically compared to previous zones. The dominant species shifted to *A. formosa* and *A. granulata*, with average relative percentage contents of 17.1% and 18.4%, respectively. The abundance of *C. dubius* decreased to about 12.9%. Other planktonic species such as *C. tholiformis*, *S. parvus*, *S. invisitatus*, and *D. pseudostelligera* all decreased in abundance. Both planktonic and benthic/epiphytic species declined during this stage.

**Zone IIb (14–7 cm, 1986–2002):** *A. formosa* relative percentage content decreased significantly, almost disappearing at the top of this zone. *A. granulata* and *A. ambigua* also declined, although *C. dubius* concentration changed little. Some planktonic species such as *S. parvus*, *C. tholiformis*, *S. invisitatus*, and *D. pseudostelligera* showed noticeable increases. Epiphytic species *Nitzschia* spp., particularly *N. palea*, suddenly appeared and accounted for about 18.4% of the percentage content. Benthic species abundance increased while planktonic species abundance decreased, with the P/B ratio showing a clear decline compared to before 1986.

**Zone IIc (7–0 cm, 2002–2012):** The most obvious change was the significant increase in *F. crotonensis* relative percentage content, from less than 3.2% at the bottom to a maximum of 28.3% at the top. *A. granulata* also increased compared to Zone IIb, while *A. ambigua* average percentage content decreased to about 15.2%. *N. palea* almost disappeared after entering this zone. *Stephanodiscus medius* suddenly increased to about 3% at the top. Overall, planktonic species abundance increased while epiphytic species abundance decreased, with the P/B ratio rising compared to the previous stage.

[Figure 4: see original paper] Diatom relative percentage concentrations (including relative abundances >1%) and P/B variation curves of core JPS2

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## 4. Discussion

Diatom identification and analysis results from Jingpo Lake show several significant assemblage shifts over the past 130 years. Under long-term environmental change, sedimentary diatom assemblages at any given horizon represent an integrated response to environmental conditions over a certain period, including watershed surface weathering, hydrological conditions, etc. [15]. According to meteorological station data from Mudanjiang, the multi-year average temperature in this region has increased by approximately 1–3°C over the past 60 years, with both annual and winter temperatures rising. Concurrently, agricultural development, deforestation, and other human activities have strongly influenced catchment surface conditions in the Jingpo Lake basin. How diatom taxonomic changes in Jingpo Lake respond to climate fluctuations and human activities requires further discussion.

### 4.1 Diatom Response to Climate Change in Jingpo Lake

Numerous studies have found that algal growth and community structure changes are closely related to climatic factors such as temperature variation, ice cover, solar radiation, and cloud cover [24–27]. These climatic factors indirectly affect diatom growth and population assemblage changes by altering water column stratification and mixing status, as well as light and nutrient conditions [16]. As long as climate-induced ecological changes exceed ecological thresholds, algal communities will respond. Significant ecological effects of climate warming have been observed in many polar and subpolar lakes [11–14, 16], mainly manifested as increased relative abundance of fast-growing small *cyclotelloid* species and decreased relative abundance of slow-growing, fast-sinking *Aulacoseira* species or small benthic *fragilarioid* species. Similar to high-latitude regions, many high-altitude lake diatom records also clearly reflect climate warming signals [28–33].

Although many mid-latitude lakes have shown similar ecological shifts [34–36], diatom assemblage responses to recent climate warming are not obvious in some regions due to multiple environmental pressures [16]. In Jingpo Lake, small planktonic species such as *C. dubius* and *C. tholiformis* began to decrease substantially from the mid-1960s, while facultative planktonic *Aulacoseira* species increased correspondingly. Based on diatom assemblage changes in high-latitude regions, this shift should indicate reduced water column stratification or enhanced vertical water disturbance. However, continuously rising temperatures in recent decades make it difficult to form such changes in water thermodynamic and hydrodynamic properties.

Habitat changes often cause biotic community structure changes. The lake

environment includes littoral zones and open water areas—two habitats that are far apart, but drastic water level fluctuations can cause them to transform into each other. Although Jingpo Lake water level data are lacking, sediment grain size distribution can reflect water level changes [37]. Jingpo Lake sediment records show that the clay component (<4  $\mu\text{m}$ ) percentage correlates with annual precipitation variation trends, while the silt component (4.0–32.0  $\mu\text{m}$ ) shows the opposite trend. Increased precipitation can raise lake levels, causing more fine-grained material to deposit in deep-water areas. Grain size components from the JPS2 core suggest that Jingpo Lake was in a low water level period during the 1960s–1980s, and in a high water level period during the 1980s–2000s (Figure 6). However, the P/B ratio contradicts this water level rise inference, indicating that water level fluctuation is not the key factor driving diatom community structure changes in Jingpo Lake.

Previous studies have shown that the transition between small diatom taxa (*Cyclotella* and *Cyclostephanos*) and large diatom taxa (*Aulacoseira*) is also evident in monsoon-affected lakes [16]. Wang et al. [38–39] found that changes in *Discostella stelligera* and *Aulacoseira* in Huguangyan Maar Lake and Erlongwan reflected East Asian winter monsoon strength. Monsoon intensity affects regional wind fields, which change water mixing status and consequently cause diatom assemblage changes. Li et al. [40] also showed that the transition between *Aulacoseira* and small planktonic species *Stephanodiscus* and *Discostella* in Jingpo Lake can indicate wind speed changes on a millennial scale. Comparison of *Aulacoseira* and small planktonic species percentages in the JPS2 core reveals that wind speed variation trends are similar to *Aulacoseira* abundance changes but opposite to small planktonic species abundance changes (Figure 7). Therefore, this study concludes that wind-induced water disturbance is an important factor affecting diatom community structure changes in Jingpo Lake.

[Figure 5: see original paper] Comparison between annual precipitation and grain-size components of core JPS2 (1951–2011)

[Figure 6: see original paper] Grain-size distribution curves of core JPS2

[Figure 7: see original paper] Comparing average wind speed from May–November (MJJASON) with percentage abundances of genus *Aulacoseira* and small-type planktonic species from core JPS2 (1951–2011)

## 4.2 Diatom Response to Human Activities in Jingpo Lake

Nutrients are key factors affecting diatom community structure changes. A major shift in Jingpo Lake's diatom community was the sudden rapid increase of *A. formosa*. Although *A. formosa* is considered to have wide nutrient tolerance [41], studies show it responds sensitively to nutrients, particularly nitrogenous nutrients [42–43], and its dominance is often associated with substantial pollution source inputs in many lakes [43–46].

Wang et al. [39] found in their study of Erlongwan sediments that *A. formosa* replaced small diatom taxa (*cyclotelloid*) around the 1980s–2000s, closely related

to temperature changes, with P/B ratios increasing alongside temperature rise [47]. However, field and experimental studies have found that P/B ratios and changes in epiphytic diatom relative abundance cannot be simply interpreted as climate change but must consider different diatom survival strategies [15-16].

*Nitzschia palea* is a typical eutrophic species that commonly appears in polluted or eutrophic water bodies [48], so its abundance increase likely relates to increased water pollutants. *Fragilaria crotonensis* is also considered a typical eutrophic species, with its rapid reproduction closely related to human activities [49-52]. Compared to *A. formosa*, *F. crotonensis* has stronger competitiveness for phosphorus [53-54].

According to surveys, although chemical fertilizers began to be used in the 1960s (mainly nitrogen fertilizer), they only became major agricultural inputs in the 1970s, with phosphorus fertilizer use increasing in the 1980s [55]. While Ning'an County fertilizer usage data are unavailable, Heilongjiang Province statistics show that chemical fertilizer application increased more than tenfold in the 1960s [55]. A 2007 water quality survey showed that total nitrogen and total phosphorus in Jingpo Lake already exceeded standards, indicating serious eutrophication [7]. These data suggest that successive increases in *A. formosa*, *N. palea*, and *F. crotonensis* abundances are largely related to extensive agricultural fertilizer use in the catchment. Domestic sewage and industrial wastewater have become two major pollution sources for Jingpo Lake [6], so urban sewage discharge impacts on diatom community structure cannot be ignored.

Diatom community structure can also change due to predation by upper trophic levels. Jingpo Lake has documented maximum fish catches since the 1960s, with artificial stocking enhancing fish populations [56]. The large lake area where the sampling site is located is dominated by small fish species (*Erythroculter mongolicus* and *Plagiognathops microlepis*) [57]. *Plagiognathops microlepis* lives in the middle-lower water layers, feeding mainly on detritus and periphytic algae [58], and is thought to have minimal impact on diatom communities. *Erythroculter mongolicus* is a carnivorous fish feeding on cladocerans [59]. Jingpo Lake diatoms are dominated by planktonic species living in open water. While fish predation on cladocerans could reduce grazing pressure on diatoms, particularly small diatoms (1-20  $\mu$ m), potentially affecting diatom community structure, sediment records show small diatom abundance only slightly increased from the 1980s-2000s, indicating fish impacts have not been a key factor changing Jingpo Lake's diatom community structure.

### 4.3 Regional Lake Diatom Record Comparison

Approximately 280 km southwest of Jingpo Lake, Xiaolongwan's sediments show increased small planktonic species *Discostella woltereckii* abundance since 1960, with decreased *Asterionella* and *Cyclotella* [47]. About 10-15 km from Xiaolongwan, Erlongwan shows increased small planktonic diatom *Discostella* while large diatom *Aulacoseira* decreased, indicating strengthened water col-

umn stratification due to temperature rise [39]. Xiaolongwan and Erlongwan are in the same climate zone with similar lake surface elevation, so they experience similar climate conditions. Under similar climatic influences, their diatom records show opposite transformation processes compared to Jingpo Lake, indicating that watershed and internal lake differences are another important factor affecting diatom assemblage changes in Northeast China's mountain lakes.

Xiaolongwan and Erlongwan are closed lakes with very small surface areas (0.1 km<sup>2</sup> and 0.15 km<sup>2</sup>, respectively) and catchment areas (0.1 km<sup>2</sup> and 0.4 km<sup>2</sup>, respectively) [61]. Jingpo Lake is an open lake with a catchment area of 11,820 km<sup>2</sup> [17] and a surface area 2–3 times larger than Xiaolongwan and Erlongwan. Differences in lake and catchment morphology may lead to differences in lake hydrodynamics and thermodynamics, making Xiaolongwan and Erlongwan more sensitive to climate change. Although diatoms in Erlongwan more or less reflect human activity impacts, and pollen records show enhanced agricultural activity and frequent forest logging in the Longgang volcanic region since the 1930s [61], regional vegetation changes have minimal impact on Xiaolongwan's diatom assemblage changes [47]. Xiaolongwan sediment trace elements and spheroidal carbonaceous particles indicate atmospheric deposition pollution began around 1970, but diatoms did not respond [47]. This suggests that because Xiaolongwan's catchment area is very small and its catchment surface has not been severely damaged, weak human disturbance has not exceeded the lake's ecological threshold, so diatoms mainly reflect regional (climate) factors rather than local factors. In contrast, Jingpo Lake's vast catchment experiences human activities that are far more intense and prolonged, with rapid urbanization and tourism development. Therefore, climate change impacts may be masked by intense human disturbance.

[Figure 8: see original paper] Changes in the abundances of main diatom species, P/B ratios, and temperature in Lake Xiaolongwan and Erlongwan [39, 47]

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## 5. Conclusion

Jingpo Lake's diatom record over the past century shows several significant community assemblage shifts. The rapid decrease of small planktonic species *C. dubius* beginning in 1966, accompanied by increased facultative planktonic taxa *A. granulata* and *A. ambigua*, indicates that increased lake surface wind speed caused water disturbance enhancement. The successive increases of *A. formosa*, *N. palea*, and *F. crotonensis* reflect nutrient enrichment from agricultural and urban development in the Jingpo Lake catchment.

Although 60 years of meteorological data show continuous temperature rise in the Jingpo Lake region, diatom assemblage changes do not show this climate signal. In contrast, Xiaolongwan and Erlongwan in the same climate zone show diatom records of increased small diatom abundance accompanying temperature rise, consistent with many polar, subpolar, and treeline lake diatom records.

Compared to Jingpo Lake, Xiaolongwan and Erlongwan have very limited human disturbance, and their small lake volumes and catchment areas make them more sensitive to climate change. This study suggests that in Northeast China, lakes with weak human disturbance (like Xiaolongwan and Erlongwan) can more clearly reflect climate warming impacts on lake ecosystems, while in lakes with strong human impacts, climate warming ecological effects are likely masked by intense human disturbance.

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