Nutrient Cycling and Productivity in Antarctic Lakes

Shabnam Choudhary, G. N. Nayak, and Neloy Khare

Abstract Sedimentary organic matter from the Antarctic lakes is the source of various proxies used to study productivity changes. A total of three sediment cores (GL-1, V-1, and L-6) collected from the lakes of Schirmacher Oasis, East Antarctica, were analysed for total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), biogenic silica (BSi) and their ratios were computed to understand the nutrient cycling and productivity in Antarctic lakes. In core GL-1 and V-1, high TOC and high clay in the upper section of the core indicated high primary productivity due to the lakes' exposure to the ice meltwater influx. The C/N ratio of substances GL-1, V-1, and L-6 varied from 2.72 to 8.52, indicating the source of organic matter as autochthonous exclusively derived from algae (C/N < 10). N/P ratio is <7.81 in all three lakes, meaning a potential limitation of N in all the lakes. In cores GL-1, V-1, N/Si ratio is lower than 1, indicating N limitation, while in core L-6, N/Si ratio is higher than 1, i.e. 1.53, indicating Si limitation. Si/P ratio is found to be greater than 3 in all the cores, indicating P limitation. Deviation from the Redfield ratio suggested that the lakes are oligotrophic.

Keywords Nutrients · Algae · Carbon · Nitrogen · Phosphorus · Sediment · Redfield ratio

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1 Introduction

Antarctica, the southernmost continent on planet earth, played an essential role in its climate system. It consists of a large number of glacial landforms such as mountain tops and nunataks. Along with these landforms, ice-free areas known as "dry valleys or Antarctic oasis" occurs commonly in the Antarctic region and are surrounded by the Antarctic ice sheet. These valleys or oasis are situated between the Antarctic ice shelves and ice sheet. These ice-free regions of Antarctica viz. McMurdo dry valleys, Bunger hills, Vestfold Hills, Larsemann Hills, and Schirmacher Oasis occupies about 2% of the Antarctic landmass and consist of numerous lakes. In recent years, these lakes have gained importance as they present pristine conditions, act as an essential source for paleo-archives, and are easily accessible in ice-free areas.

In general, lake sediments are ideal repositories of eolian and fluvial materials. The sediment input through glacial meltwater and biological productivity is the primary source of sedimentation in Antarctic lakes. The biological productivity is confined primarily to algae and cyanobacteria in the Antarctic lakes (Yoon et al. 2006; Smith et al. 2006; Hodgson et al. 2009; Choudhary et al. 2018b). During the austral summer, lake sedimentation is predominant (Simmons et al. 1986); hence, transferring the detrital matter from the Antarctic landmass to its lakes, meltwater seems to play an important role. Significantly lower sediment accumulation rates are observed in high-latitude lakes than temperate lakes (Wolfe et al. 2004).

The source and accumulation of organic matter can be identified by studying the abundance of total organic carbon and total nitrogen in lacustrine sediments. The type and amount of sedimentary organic matter can reflect the past fluctuations in lake's productivity and terrestrial inputs influenced by climate-induced environmental changes (Talbot and Johannessen 1992; Meyers 1997; Leng and Marshall 2004). Carbon, Nitrogen, and Phosphorus are the primary archives extracted from lake sedimentary organic matter to understand the limiting factor affecting algal growth. These robust proxies are indicators of organic matter's provenance, the type and amount of organic matter that has been deposited in the lake over a while (Talbot and Johannessen 1992; Meyers 1997; Leng and Marshall 2004). The C/N ratio of organic matter is also used as an indicator of the source of organic matter (Talbot 2001; Meyers 2003). Past environmental conditions (redox) in the lacustrine systems due to climate change can be deciphered from the TOC and TN of bulk sedimentary organic matter (Talbot and Johannessen 1992). The molar concentrations of C, N, and P have been used to estimate which of these nutrients is limiting the growth of algae in aquatic systems compared to the Redfield ratio. Redfield observed that phytoplankton contains a molecular C:Si:N:P ratio of 106:15:16:1 (Harrison et al. 1977). A departure from this ratio has been assumed to imply nutrient deficiency. The use of elemental ratios has become widespread in marine and freshwater phytoplankton studies. In the present study, three lake sediment cores from the Schirmacher Oasis, East Antarctica, have been studied for understanding the cycling of the nutrients controlling the primary productivity in the lakes. As in the lakes, nutrients rather than physical conditions tend to limit primary productivity.

2 Nutrient Cycling in Lakes

In an ecosystem, nutrient cycling is an essential process that describes the usage of the nutrients, their movement, and the methods and their recycling in the environment (Fig. 1). For an organism's existence, nutrients like carbon, oxygen, hydrogen, phosphorus, and nitrogen are essential and are termed macronutrients. Nutrient cycles involve living organisms and non-living components and biological, geological, and chemical processes. Thus, these nutrient cycles are also known as biogeochemical cycles. Biogeochemical cycles can be categorised into two main types: global cycles and local cycles. Elements such as carbon, nitrogen, oxygen, and hydrogen are recycled through abiotic environments, including the atmosphere, water, and sediment.

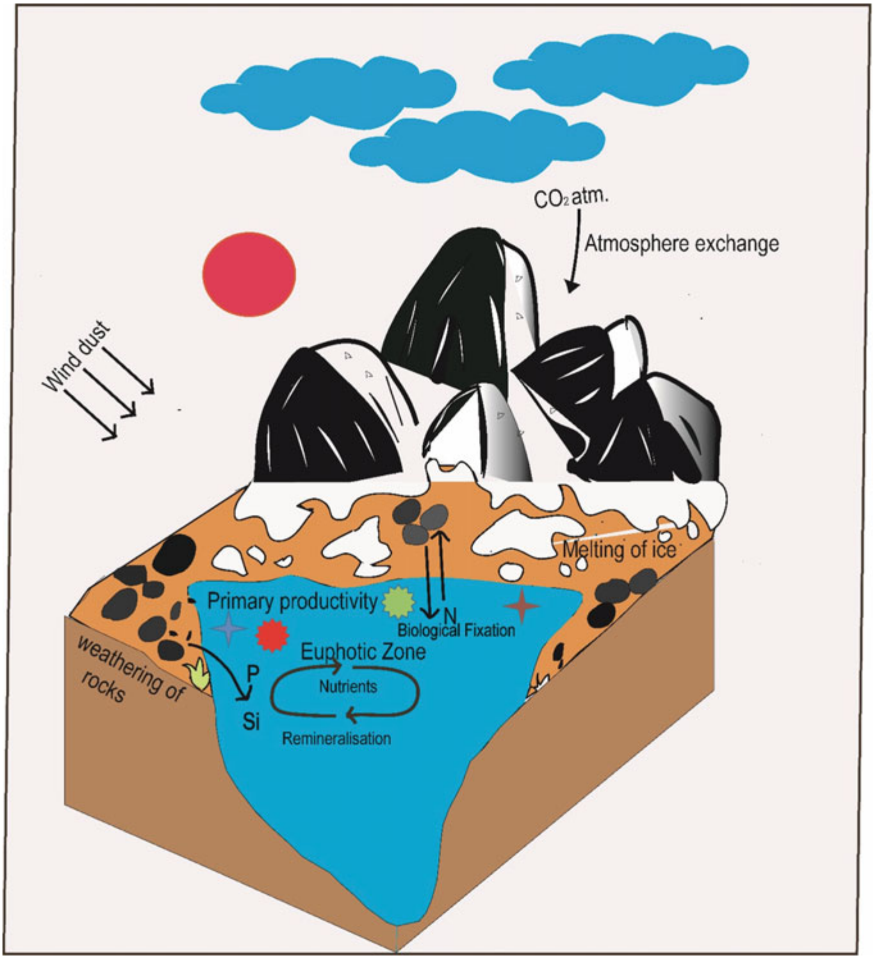

Fig. 1 Nutrient cycling in lakes

The atmosphere is the primary abiotic environment. Most of the elements enter the cycle from the atmosphere and travel long distances before the organisms' uptake in a cycle (Inagaki and Ishizuka 2011). The sediment is the primary abiotic environment for recycling elements such as phosphorus, calcium, and potassium. As such, their movement is typically over a local region.

The nutrient cycle allows the transformation of the element into different specific forms that enable utilising other organisms' particular component. Example, although nitrogen is abundant in the atmosphere, plants can only uptake nitrogen in two solid forms, viz. ammonium and nitrate. Without the transformation of nitrogen into these usable forms, the growth of an organism would be limited. The transfer of elements from one location to another is also aided by nutrient cycles. Some features are highly concentrated in an inaccessible area to most living organisms, such as nitrogen in the atmosphere. Through the nutrient cycle, these elements are transferred to accessible locations such as the sediment. The nutrient cycle facilitates the storage of features in their natural reservoirs and is released to the organisms in the required amounts. For example, through the nitrogen cycle, organisms can use nitrogen in quantities suitable even though it is abundant in the atmosphere. It is a chain through which living and non-living things are linked to each other and are dependent on one another for their survival. As the nutrient cycles pass through different spheres, viz. biosphere, lithosphere, atmosphere, and hydrosphere, the flow of elements is regulated. Each sphere has a particular medium, and the rate at which the flow of elements is regulated is determined by the medium's viscosity and density (Dommain et al. 2014). Therefore, the elements flow at different rates within the cycle. In an aquatic ecosystem, weathering of rocks is one of the essential sources of nutrients. However, through weathering, nutrients have been added to the ecosystems in relatively smaller quantities over a more extended period. Essential nutrients released by the weathering of rocks include Calcium, Magnesium, Potassium, Sodium, Silicon, Iron, Aluminum, and Phosphorus (Kumar and Sekaran 2014). The atmosphere also contributes a considerable amount of nutrients to the ecosystem through precipitation or different biological processes.

Nutrient concentrations vary considerably in the Antarctic Lakes, and phosphorus appears to be a limiting nutrient for phytoplankton production in many cases (Laybourn-Parry 2003). Thus, the nutrient limitation is a significant characteristic of most of the Antarctic lacustrine systems. Although physical factors such as low light and temperature are substantial constraints on production in most lakes, the nutrient limitation can also be significant. Therefore, most of the lakes are oligotrophic (Choudhary et al. 2018b) and ultraoligotrophic with a shallow photosynthesis rate (Vincent and Layborn-Parry 2008).

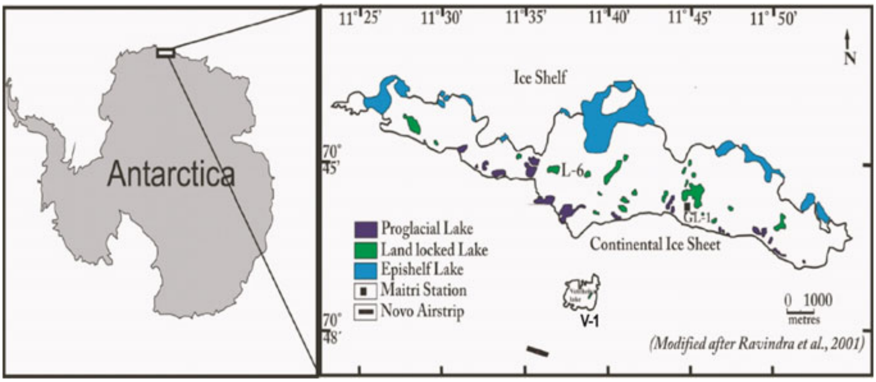

Fig. 2 Map of Antarctica showing the location of Schirmacher oasis and map of Schirmacher Oasis (modified after Ravindra et al. 2001) showing the sampling locations in the study area

3 Materials and Methodology

3.1 Study Area and Sample Collection

The samples were collected from Schirmacher Oasis (Fig. 2) during the 31st Indian Scientific Expedition to Antarctica, January 2012. Sediment core samples of varying length 40 cm (GL-1), 32 cm (V1), and 58 cm (L-6) were retrieved manually from near the periphery of the lake when the lakes were ice-free. A PVC handheld corer was inserted by hammering manually into the lake sediment bed and then retrieved. Further, the cores were labelled, packed, and stored in a deep freeze at <4 °C. The cores were transported to the laboratory, core GL-1 and V-1 subsampled at 4 cm interval while L-6 was subsampled at 2 cm and later on dried at 60 °C.

3.2 Sample Analysis

For determination of total organic carbon (TOC) small portion of each subsample was powdered and homogenised in an Agate mortar. TOC was determined using the Walkey Black method (Walkey 1947), adopted and modified by Jackson (1958), which utilised exothermic heating and oxidation with potassium dichromate ($K_2Cr_2O_7$) and sulfuric acid (H_2SO_4). The freeze-dried sediment sample was also analysed for total nitrogen (TN) concentration in the Marine Stable Isotope Lab (MASTIL) at National Centre for Antarctic & Ocean Research, Goa, India, using an EA (Isoprime, Vario Isotope Cube). The precision for N% was ±0.63% (1σ standard deviation) obtained by repeatedly running sulfanilamide as the standard. Calcium carbonate was computed using the values of Ca analysed through the atomic absorption spectrophotometer. Biogenic silica (BSi) from the freeze-dried sample was extracted using 25 ml of 1% Na_2CO_3 in an 85 °C water bath for 5 h and measured by the wet alkaline extraction method, modified by Mortlock and Froelich (1989) and Muller and Schneider (1993) where the intensity of blue silico molybdenum complex was measured at 810 nm using UV-1800 (Shimadzu) visible spectrophotometer. Duplicate measurements were conducted on each sample, and relative error was noted to be less than3%. The sediment sample was digested using HF:HNO_3:$HClO_4$ mixture for total phosphorus analysis and brought to liquid phase as adopted by Yu et al. (2013) and further determined following the procedure given by Murphy and Riley (1962) where the intensity of phospho-molybdenum blue complex was measured at 880 nm using UV-1800 (Shimadzu) visible spectrophotometer. The accuracy of phosphorus analysis was determined using a digested sample of JLK-1, and relative error was noted to be less than 4%.

4 Source of Sedimentary Organic Matter in Lacustrine Sediments

Sedimentary organic matter offers different proxies that can be used to reconstruct past environmental changes as preservation and production of organic matter is affected by the environmental changes to a more considerable extent (Meyers 1997). Organic matter preserved in lake sediments reflects the ecological changes. In core GL-1 and V-1 (Fig. 3), high TOC along with high clay in the upper section of the core indicated high primary productivity due to the exposure of lakes to the ice melt-water influx (Choudhary et al. 2018a). C/N ratios have been used often to identify the source of organic matter in lake sediments (Talbot and Johannessen 1992; Meyers 1997). Algae and cyanobacteria typically have an atomic C/N ratio between 4 and 10, while the terrestrial organic matter is above 20 (Meyers 1994, 2003; Meyers and Teranes 2001). The C/N ratio of cores GL-1, V-1, and L-6 varied from 2.72 to 8.52, indicating the source of organic matter as in situ exclusively derived from algae (C/N < 10) as per the classification of Meyers (1994). The C/N ratio for all three cores was less than 10 for the entire core length, indicating that the significant organic matter source was autochthonous. However, a high C/N ratio in core GL-1 at a depth of 16 cm and the surface showed prolonged ice-free conditions. It increased meltwater influx which must have delivered terrestrial organic matter to the lake, possibly from lichens and mosses (Choudhary et al. 2018a). Also, the loss of N from the sediments during diagenesis or nitrogen limitation in the surface water due to high primary production must have resulted in the relatively large range of the C/N ratio. Partial degradation of algal organic matter can selectively diminish proteinaceous components and thereby raise C/N ratios. During early diagenesis, selective degradation of organic matter components can modify C/N ratios of organic matter in sediments (Meyers 1997).

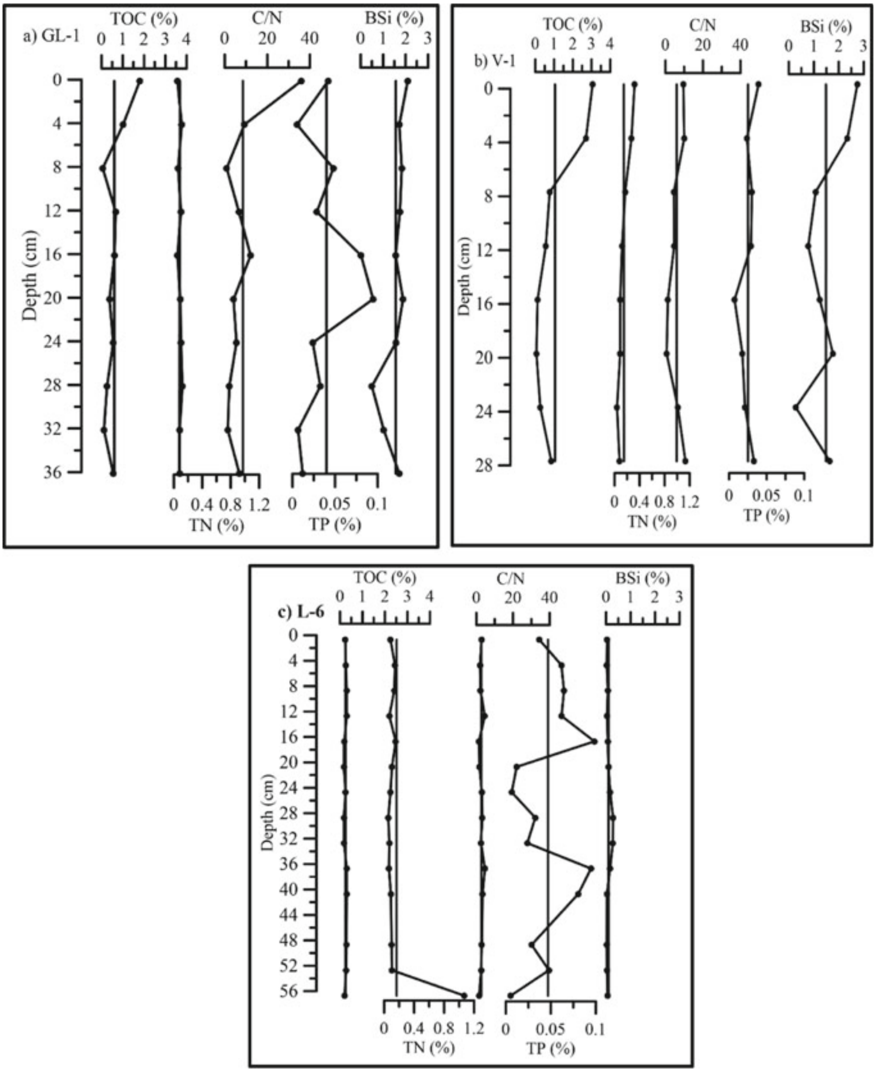

Fig. 3 Carbon, nitrogen, phosphorus and biogenic silica concentration in the core **a** GL-1. **b** V-1. **c** L-6

4.1 Nutrient Limitations in Lakes

In lakes where nutrients rather than physical conditions tend to limit algal growth leading to changes in productivity, the molar concentrations of carbon, nitrogen, and phosphorus (Table 1) have been used to estimate nutrient limitation (Choudhary et al. 2018b). The least available nutrient in any system is considered to be the limiting nutrient for the total amount of photosynthetic C-fixation that a system can sustain.

Table 1 Molar ratios of carbon/nitrogen, nitrogen/phosphorus, nitrogen/silica, and silica/phosphorus contents of cores (a) GL-1 (b) V-1 (c) L-6

Cores	TOC/TN	TN/TP	TOC/TP	TN/Si	Si/P
GL-1	7.30	2.47	14.03	0.03	80.46
V-1	5.14	4.05	31.49	0.05	73.21
L-6	2.21	7.81	4.04	1.53	4.71

This is a stoichiometric concept that presumes that one nutrient is consumed before other nutrients. It is considered that P is limiting in lakes, while N is usually limiting in the marine environment. However, there are exceptions; among P, N and Si, any of these nutrients can be limiting (Hecky and Kilham 1988).

Redfield surmised that the C:N:P ratio is 106:16:1 under ordinary conditions, when neither of the nutrients is limiting (Redfield 1934, 1958; Sterner and Elser 2002; Choudhary et al. 2018b). A deflection from the particular ratio attributes to the deficiency of C, N, or P in an aquatic system. Harrison et al. (1997) suggested that siliceous microorganisms like diatoms need silicate to form the hard part of their shell known as frustule, and an optimal C:Si:N:P ratio is 106:15:16:1. When the C/N molar ratio was compared with the Redfield ratio, it was lower in all three lakes. C/N ratios typically <10 indicate algal growth suggesting autochthonous lacustrine organic matter, whereas ratios above 20 may be >200 suggested allochthonous organic matter (Talbot and Johannessen 1992). In all three cores, as stated earlier, the C/N ratio is lower than 10, indicating algal growth and the autochthonous nature of organic matter. Further, the N/P ratio above 17 indicates P limitation; a ratio below 10 suggests N limitation, and values between 10 and 17 indicate that either of the nutrients may be limiting suggested by Ulen (1978) and Hellstrom (1996). In the present study, the N/P ratio is <7.81 in all the three lakes, namely core GL-1, V-1, and L-6, which is much lower than 16, indicating a potential limitation of N in all the lakes. This limitation of N may be either due to phosphorus incorporation into the sediments, reducing the N/P ratio or removing nitrogen by denitrification in water column or sediments (Tyrrell and Law 1997; Downing and McCauley 1992; Choudhary et al. 2018b). Further, the C/P molar ratio varied from 4.04 to 31.49 in these lakes, higher than the Redfield ratio observed by Dore and Priscu (2001) in McMurdo dry valley lakes Antarctica. According to Harrison et al. (1977), N/Si > 1 and Si/P < 3 are indicative of Si limitation. In cores GL-1, V-1, N/Si ratio is lower than 1, indicating N limitation, while in core L-6, N/Si ratio is higher than 1, i.e. 1.53, indicating Si limitation. Si/P ratio is found to be much higher than 3 in all the cores that indicated P limitation. Priscu's (1995) experimental work demonstrated that Lake Vanda and Lake Bonney in McMurdo dry valleys are phosphorus-deficient while Lake Fryxell and Lake Hoare are nitrogen deficient. The ratio of nutrients C, N, P, and Si deviated from the Redfield ratio and showed low concentrations suggesting that the lakes are oligotrophic, leading to low rates of plankton biomass and low primary production despite relatively high temperature, ice-free conditions of the lake, and high influx of sediment. The nutrient concentrations are low in all three lakes due to less organic matter concentration as it might have been diluted by coarse-grained sediment. They might also be related to glacial meltwater being low in nutrient concentrations.

Although data generated from the limnetic ecosystems does not fit the Redfield paradigm very well as marine data, because in the open ocean, the particulate organic carbon of the surface oceans is dominated by phytoplankton that follows Redfield stoichiometry, the terrigenous organic matter with higher C/P and C/N can contribute significantly to the pool of organic carbon available for remineralisation to offset the C:N:P ratio in some lakes. Also, bacterial denitrification and N-fixation can affect N/P ratios.

5 Factors Affecting Nutrient Concentrations and Primary Productivity

Climate change has directly affected the Antarctic aquatic systems primarily. During the austral summer, with warming conditions in the region due to the retreat of glaciers in the study area, higher melting occurs, leading to a sizeable freshwater influx to the lakes. As the lakes are ice-free, they are getting exposed to the atmosphere. Atmosphere exchange enhancing CO_2 input decreased ice cover (improving photosynthetically active radiation). High temperature has increased nutrient influx and increased primary productivity in lakes (Lyons and Finlay 2008; Choudhary et al. 2018b).

Nutrient chemistry is modified to a more considerable extent by the streams coming out from the melting glaciers and draining into the lakes. The chemistry of the nutrients can also be affected by supraglacial processes (Vincent and Laybourn-Parry 2008). Recent studies in the Taylor Valley (MacMurdo dry valley) aquatic systems suggested that the C:N:P stoichiometry is affected primarily as water flows through the hydrological sequence from snow/glacier/ice to the closed basins, i.e. lakes. Streams flowing on younger surfaces exposed in the catchment area provide more phosphorus relative to nitrogen, and streams with high abundances of algal mats have a much lower N:P ratio (Lyons and Finlay 2008). Nitrogen fixation, i.e. conversion of atmospheric N_2 to NO^{3-} occurs in the microbes' catchment area while weathering of the continental rocks contributes to phosphate. Therefore, nitrogen and phosphate concentrations are regulated by runoff from the land (Meyers 1997).

The age and history of a landform and the gradient and geomorphology of the streams also play an essential role in regulating the nutrient input into the lakes and ultimately primary productivity (Lyons and Finlay 2008).

6 Conclusions

In the studied Antarctic lakes, organic matter is found to be autochthonous exclusively derived from algae, with significant terrestrial organic matter contribution at some intervals derived from the lichens and mosses growing around the lake. The ratio of nutrients C, N, P, and Si deviated from the Redfield ratio showed low concentrations suggesting that the lakes are oligotrophic, leading to low plankton biomass rates and low primary production despite relatively high temperature, ice-free conditions of the lake, and high influx of sediment. Low nutrient concentrations in all three lakes may be due to inadequate organic matter concentration. The terrestrial material might have diluted it and might also be related to glacial meltwater, devoid of nutrient concentrations.

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