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Model estimates of the contributions of interannual changes of climate and nutrient load to changes in the Lake Ladoga ecosystem in 1980–2020

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Abstract

Quantitative estimates of the Lake Ladoga ecosystem response to changes in climatic atmospheric forcing and external nutrient loads were obtained for the period 1980–2020. The estimates were obtained using the MITgcm three-dimensional hydrothermodynamic model combined with the SPBEM biogeochemical module adapted to the phosphorus-limited conditions of the lake.

Numerical experiments were conducted using the following three scenarios: 1) a reference scenario with realistic changes in the external nutrient load and atmospheric forcing for 1980–2020, 2) with realistic changes in the external nutrient load and the "average" intra-annual course of atmospheric forcing for this period, and 3) with realistic changes in atmospheric forcing and a constant external nutrient load equal to the average value for the period under consideration.

The results of the study demonstrate a pronounced dominance of the external nutrient load as the main factor determining the dynamics of the lake ecosystem characteristics in 1980–2020. The contribution of climate change to the highly deterministic linear trends of the change in winter phosphate concentrations, summer phytoplankton biomass, and annual phytoplankton production in the photic layer amounted to only 24 %, 10 %, and 21 %, respectively. According to the calculation results, there is a noticeable decrease in these characteristics of the lake ecosystem in the second half of the considered period 1980-–2020. At the same time, a noticeable (more than 20 %) compensating effect of climate change is noted for phytoplankton production, leveling out part of the effect of the decrease in nutrient load.

It is shown that non-diatoms, which make the main contribution (63 %) to the total phytoplankton production, strongly respond to climatic changes in water temperature in the considered period. Diatoms show less dependence on climate change, maintaining a close relationship with winter phosphate reserves.

Keywords: lake ecosystem, climate, external nutrient load, mathematical modeling, Lake Ladoga

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Модельные оценки вкладов изменений климата и биогенной нагрузки в изменения экосистемы Ладожского озера в 1980–2020 гг.

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Аннотация

Получены количественные оценки реакции экосистемы Ладожского озера на изменения климатических атмосферных воздействий и внешней биогенной нагрузки в период 1980–2020 гг. Для их получения использована трехмерная модель гидротермодинамики MITgcm, объединенная с биогеохимическим модулем SPBEM, адаптированным для фосфоро-лимитированных условий озера.

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Численные эксперименты проведены по трем следующим сценариям: 1) опорному с заданием реалистичных изменений внешней биогенной нагрузки и атмосферных воздействий в 1980–2020 гг.; 2) с заданием реалистичных изменений внешней биогенной нагрузки и «среднего» внутригодового хода атмосферных воздействий для этого периода; 3) с заданием реалистичных изменений атмосферных воздействий и постоянной внешней биогенной нагрузки, равной среднему за рассматриваемый период значению.

Результаты работы демонстрируют выраженное доминирование внешней биогенной нагрузки как основного фактора, определяющего динамику характеристик экосистемы озера в 1980–2020 гг. Вклад изменений климата в высоко детерминированные линейные тренды изменения зимней концентрации фосфатов, летней биомассы фитопланктона и годовой продукции фитопланктона в фотическом слое составил всего лишь соответственно 24 %, 10 % и 21 %. Согласно результатам расчётов, происходит заметное уменьшение указанных характеристик экосистемы озера во второй половине рассматриваемого периода 1980–2020 гг. При этом для продукции фитопланктона отмечается заметное (более 20 %) компенсирующее влияние климатических изменений, нивелирующее часть эффекта от снижения биогенной нагрузки.

Показано, что недиатомовые водоросли, вносящие основной вклад (63 %) в суммарную продукцию фитопланктона, сильно реагируют на климатические изменения температуры воды в рассматриваемый период. Диатомовые водоросли демонстрируют меньшую зависимость от климатических изменений, сохраняя тесную связь с зимними запасами фосфатов.

Ключевые слова: озерная экосистема, климат, внешняя биогенная нагрузка, математическое моделирование, Ладожское озеро

1. Introduction

Lake Ladoga, the largest lake in Europe, occupies a special place among the world's great lakes not only due to its size but also due to its unique northern location between 59°54' and 61°47' N. This enormous natural reservoir and its vast catchment area play a critical economic and ecological role in the life support of Russia's northwestern region [1–3]. Ladoga's significance is multifaceted: it serves as a main source of drinking and industrial water supply for the multi-million-strong city of St. Petersburg, the Leningrad Region, and the Republic of Karelia. It is a vital link in the Volga-Baltic Waterway, providing transportation connectivity. It also possesses colossal tourism, recreation, and fisheries potential.

The ecosystem of Lake Ladoga is classified as phosphorus-limited [1], meaning that phosphorus availability is the primary factor limiting the lake's productivity. In this regard, the central place in the study of its long-term variability naturally belongs to the analysis of the phosphorus cycle. Analysis of the interannual dynamics of the external phosphorus load for the period from 1980 to 2020 (Figure 1a) reveals three clearly defined periods. The first period (1980–1992) is characterized by an extremely high level of anthropogenic phosphorus input with an average value of about 5,900 tons per year. This is followed by a short but extremely significant second period (1993–1995), during which a sharp, precipitous decrease in the load occurred. Finally, the third period (1995–2020) is marked by stabilization of the load at a significantly lower level with an average annual value of about 3,400 tons [3].

Assessments of the lake ecosystem state based on in situ observation data demonstrate that, despite a nearly twofold decrease in the external phosphorus load since 1991, the expected proportional decrease in phytoplankton biomass and primary production has not occurred [4, 5]. Existing hypotheses explaining this weak ecosystem response link it to the compensating influence of climate change. In particular, it is assumed that the effect of the increase in water temperature caused by global warming neutralizes at least partially the effect of reduced loads. This mechanism is realized, on the one hand, due to an increase in the duration of the growing season, and on the other, due to the intensification of internal processes, such as the rate of metabolism and turnover (recycling) of organic matter. Nevertheless, it is difficult to reliably confirm or refute these assumptions solely on the basis of in situ data due to insufficient spatiotemporal coverage of the lake area during its monitoring [3].

Thus, there is a clear need to employ mathematical modeling methods to assess the ecosystem's response to changes in various external factors. The aim of this study is to quantitatively assess the response of main components of the Lake Ladoga ecosystem (phytoplankton biomass and primary production, nutrient concentrations) over the period 1980–2020 to external impact scenarios that consistently exclude interannual variability in atmospheric impacts and external phosphorus loads.

2. Materials and Methods

2.1. Model

The study of the Lake Ladoga ecosystem's response under various environmental scenarios was conducted using a three-dimensional mathematical model of hydrothermodynamics combined with a biogeochemical cycle model. The Massachusetts Institute of Technology (MITgcm) model [6, 7] served as the basis for reproducing the lake's hydrothermodynamics and solving the advection-diffusion equations. Biogeochemical processes were modeled using the SPBEM model, adapted to Lake Ladoga conditions, using observation data (both in situ and remote sensing) [8]. A detailed description of the model configuration, its adaptation to the studied reservoir, and the verification procedure are presented in [8–10]. The biogeochemical module of the model describes the interactions between nitrogen and phosphorus cycles in the lake's water column and bottom sediments. The pelagic subsystem accounts for the biomass of zooplankton and two functional groups of phytoplankton (diatoms and non-diatoms), detrital nitrogen and phosphorus, dissolved organic nitrogen and phosphorus compounds of varying lability, inorganic forms of nitrogen (ammonium, nitrites, and nitrates), phosphates, and dissolved oxygen as an indicator of the balance of production-destruction processes. The bottom sediment subsystem describes the dynamics of benthic forms of nitrogen and phosphorus.

Biogeochemical interactions include a complex of key processes: primary production of phytoplankton, its consumption by zooplankton, the processes of organism mortality with the formation of detritus, the regeneration of mineral compounds through the excretion and mineralization of organic matter, the processes of mineralization of bottom sediments with the release of biogenic elements into the water column, as well as denitrification in the aquatic environment and bottom sediments. A detailed description of the equations, parameters and coefficients of the biogeochemical module is presented in [9, 10], and the features of its adaptation to freshwater phosphorus-limited ecosystems are presented in studies [8, 11].

The boundary conditions of the model included atmospheric forcing fields and river runoff data for the hydrothermodynamic module, as well as parameters of nutrient input from the atmosphere and from the catchment area for the biogeochemical module. Atmospheric forcings were specified based on ERA-5 reanalysis data [12], containing hourly values of atmospheric pressure, wind speed components, air temperature and humidity, precipitation amount, and shortwave and longwave radiation fluxes. The external nutrient load is formed due to river runoff, atmospheric deposition, point sources of pollution, and diffuse runoff, including the input of nutrients with rainwater and meltwater entering the reservoir directly. The dynamics of the external nutrient load in the interannual aspect, used in the present study, is discussed in detail in [1, 8].

2.2. Scenarios

To study the impact of interannual variability on ecosystem characteristics, calculations were performed using three scenarios.

The reference scenario (1) takes into account natural interannual variability in both atmospheric forcing and external nutrient loading. This scenario utilized ERA-5 reanalysis data [12] for the period 1980–2020 on atmospheric forcing fields and data on interannual fluctuations in external nutrient loading for the same period from [1, 8].

The second scenario (2) analyzes the ecosystem's response to interannual fluctuations in external nutrient loading. It utilized actual load data for the period 1980–2020, while atmospheric forcing was specified using the parameters of an "average" year, during which intra-annual changes in meteorological characteristics were closest to their long-term averages.

The third scenario aims to assess the impact of climate change on the lake ecosystem. In this case, the atmospheric forcing was the same as in the reference scenario, and the external nutrient load was set constant, equal to the average value for the period from 1980 to 2020.

In the reference scenario, the initial conditions for the 40-year calculation were set based on preliminary integration of the system of model equations until a quasi-equilibrium state was reached. The state was obtained with repeated atmospheric forcing and external nutrient load corresponding to 1979. In scenario 2, a similar quasi-equilibrium state was obtained with the "average" atmospheric forcing and external nutrient load of 1979, and in scenario 3, with repeated atmospheric forcing of 1979 and the average (for the period from 1980 to 2020) external nutrient load. As shown below, the procedure used for setting the initial conditions resulted in the average water temperature for the period in scenario 2 being somewhat overestimated (compared to scenario 1). In scenario 3, the initial phosphorus load was 30 % lower than in scenario 1.

2.3. Selecting an "average" year

To select the year most representative from a climatic perspective, a multicriteria time series analysis method was used. Its goal was to identify the year with meteorological characteristics closest to the long-term climatic norm.

The initial data included daily air temperature, atmospheric pressure, wind speed, and solar radiation flux for the period from 1980 to 2020. To quantitatively assess the deviations of meteorological parameters in each year from the norm, a set of metrics was used: the root mean square error, the Pearson correlation coefficient, and the mean absolute deviation. To account for time shifts and seasonal characteristics, a dynamic temporal alignment method was additionally included in the analysis.

In the final stage, an integral assessment was calculated for each year as a weighted sum of all normalized metrics. This approach allowed for an objective ranking of years and the identification of the most typical ones.

As a result, 2004 was determined to be the most representative year, which meteorological indicators showed the smallest integral deviation from the climate norm.

3. Results and Discussion

The main ecosystem characteristics that determine the trophic status of a reservoir are *phytoplankton biomass* and *primary production*, as these parameters characterize the productivity of the aquatic system and the turnover of organic matter within the food chain. Phosphorus is the limiting nutrient in the Lake Ladoga ecosystem, as confirmed by numerous studies [1, 3], demonstrating that *phosphate concentrations* determine the intensity of phytoplankton development and the degree of eutrophication. Among physical factors, *water temperature* plays a primary role, controlling the production and destruction processes of organic matter transformation. Therefore, when analyzing the obtained results, we will consider the above factors, along with phosphorus exchange fluxes (recycling and phosphorus release from bottom sediments).

3.1. Assessment of the variability of ecosystem characteristics due to interannual variability in atmospheric forcing and external nutrient loading

Figure 1 shows the interannual dynamics of the external phosphorus load, averaged temperature over the growing season (May–October), averaged phosphates for March–April, averaged phytoplankton biomass in the photic layer over the growing season, and annual primary production for the three scenarios mentioned above. In the first two scenarios, all studied ecosystem characteristics decrease in response to a decrease in the external nutrient load. Note the 4–5-year time lag between the onset of a decrease in phosphorus input from external sources and the onset of a decline in biogeochemical characteristics. This is explained by the phosphorus turnover time in the lake, which is 5.4 years [13].

A distinctive feature of scenario 2 (compared to scenario 1) is a more intense decrease in annual primary production: its linear trend is 17.2 % greater than in scenario 1 (see Table 1). This is explained by the absence of a warming-induced increase in primary production in this case. A more intense decrease in primary production with no increase in recycling, contributed to an increase in winter phosphates in the photic layer and a 24 % decrease in the trend modulus of this characteristic (Table 1). The trend modulus of phytoplankton biomass in the photic layer during the growing season also decreased, but only by 9.5 % due to the opposing effects of a lack of growth in primary production (a decline in biomass) and a lack of increased recycling (an increase in biomass) due to rising temperature.

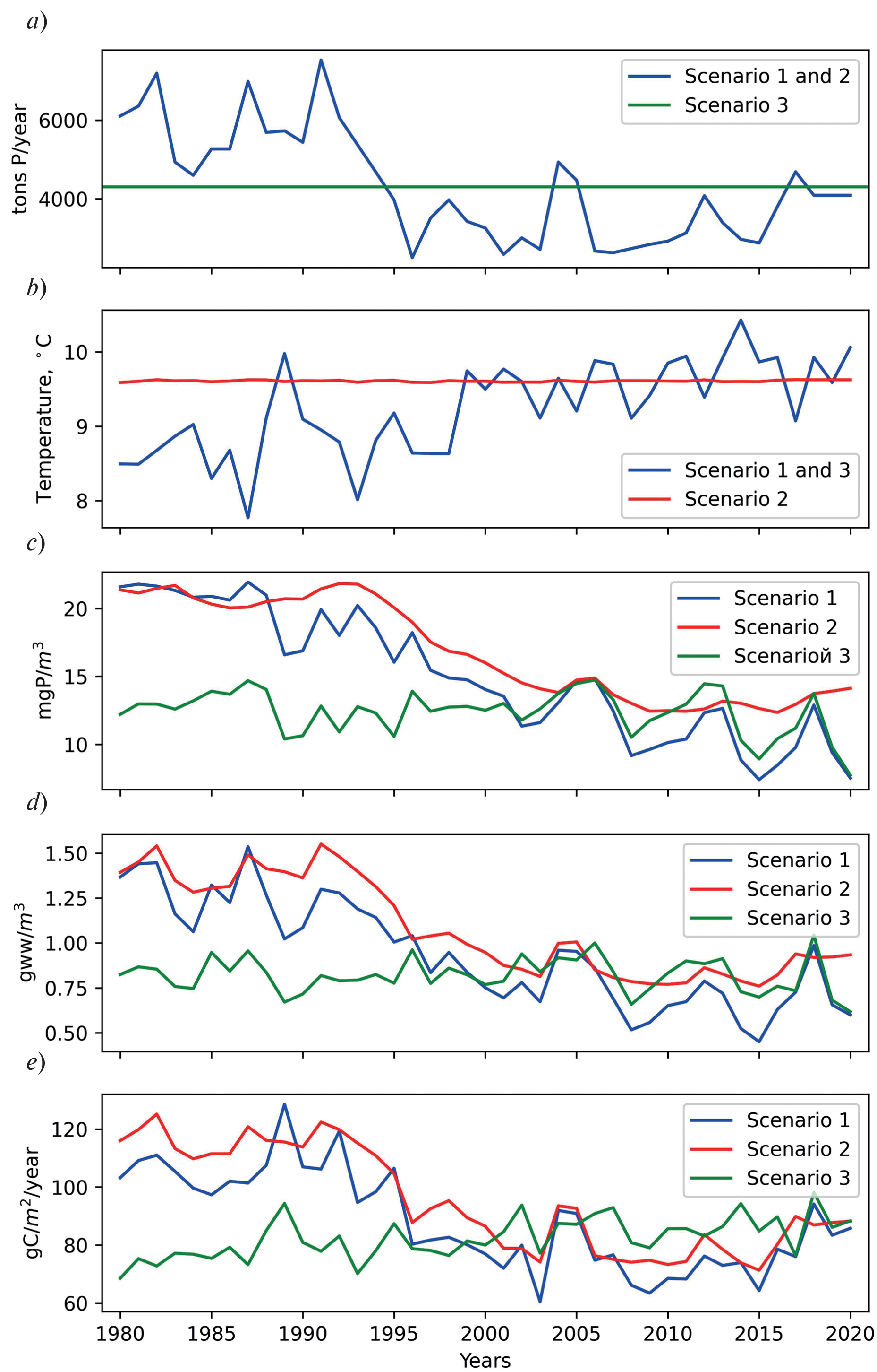

Fig. 1. Interannual variability of the annual external phosphorus load (*a*), averaged over the growing season (May-October) temperature in the photic layer (*b*), averaged over March-April phosphates in the photic layer (*c*), average over the growing season (May-October) phytoplankton biomass (*d*) and annual primary production (*e*) in scenarios 1, 2, 3

Another distinctive feature of scenario 2 is the smoother curves of interannual variability of the studied characteristics compared to scenario 1, which indicates a significant contribution of interannual changes in atmospheric impacts to the variability of ecosystem characteristics. However, the standard deviation (Table 2), calculated using the initial data of scenarios 1 and 2, does not show a decrease in the intensity of variability for all ecosystem characteristics in scenario 2. This is due to the significant influence of the linear trend on the standard deviation. When estimating the standard deviation based on time series from which the linear trend is excluded, the decrease in the intensity of interannual variability in scenario 2 becomes obvious. Thus, for winter phosphate stocks, the standard deviation in scenario 1 is 1.65 mg/m³, while in scenario 2 it is 1.43 mg/m³. For phytoplankton biomass, the standard deviation decreases from 1.52 to 1.35 g/m³, and for phytoplankton primary production, from 11.58 to 9.77 gC/(m² year).

Table 1

Linear regression equations with determination coefficients (R^2) for main ecosystem characteristics under different scenarios

	Scenario 1	Scenario 2	Scenario 3
External phosphorus load, tons P/year	–76.207t + 156684 (R^2 = 0.429) (p-value = 0.000)	–76.207t + 156684 (R^2 = 0.429) (p-value = 0.000)	4270*
Temperature (°C) of the photic layer during the growing season (May-October)	0.037t – 64 (R^2 = 0.515) (p-value = 0.000)	9.6*	0.037t – 64 (R^2 = 0.515) (p-value = 0.000)
Phosphate concentration (mg/m³) in the photic layer during the period of maximum winter accumulation	–0.363t + 741 (R^2 = 0.874) (p-value = 0.000)	–0.276t + 569 (R^2 = 0.842) (p-value = 0.000)	-0.045t + 102 (R^2 = 0.109) (p-value = 0.035)
Phytoplankton biomass (g/m³) in the photic layer during the growing season (May-October)	–0.021t + 42 (R^2 = 0.731) (p-value = 0.000)	–0.019t + 39 (R^2 = 0.743) (p-value = 0.000)	-0.001t + 2.7 (R^2 = 0.015) (p-value = 0.448)
Annual phytoplankton primary production (gC/(m² year)	–1.022t + 2131 (R^2 = 0.527) (p-value = 0.000)	–1.235t + 2565 (R^2 = 0.696) (p-value = 0.000)	0.349t – 615 (R^2 = 0.356) (p-value = 0.000)

Notes:1) * – Average values for the period 1980–2020 are given; 2) in the regression equations for interannual variability of characteristics, the variable “t” denotes years.

Table 2

Main ecosystem characteristics averaged over the period 1980–2020 and standard deviation (indicated in brackets) in scenarios 1, 2, and 3

	Scenario 1	Scenario 2	changes in% relative to scenario 1	Scenario 3	changes in % relative to scenario 1
Temperature (°C) of the photic layer during the growing season (May-October)	9.24 (0.62)	9.60 (0.00)	3.8 %	9.24 (0.62)	0 %
Phosphate concentration (mg/m³) in the photic layer during the period of maximum winter accumulation	15.01 (4.65)	16.85 (3.61)	12.3 %	12.37 (1.63)	–17.7 %
Phytoplankton biomass (g/m³) in the photic layer during the growing season (May-October)	0.93 (0.29)	1.08 (0.27)	16.1 %	0.82 (0.09)	–11.8 %
Annual phytoplankton primary production (gC/(m² year)	88.57 (16.85)	95.58 (17.73)	7.9 %	82.83 (7.01)	–6.5 %
Annual phytoplankton primary production (tons P/yr)	36920 (7024)	39842 (7390)	7.9 %	34524 (2920)	–6.5 %
Remineralization/recycling (tons P/yr)	33372 (6855)	36369 (7258)	8.9 %	31543 (2778)	–5.4 %
Phosphorus release from bottom sediments (tons P/yr)	2876 (250)	2939 (237)	2.1 %	2448 (37)	–14.8 %

In scenario 2, the average values of all characteristics (Table 2) exceed their values in the reference scenario (scenario 1). On average, over the period under consideration, the temperature of the photic layer during the growing season was higher in scenario 2 (by ≈ 0.4 °C) than in the reference scenario (see Table 2). This increase in water temperature contributed to the intensification of production and destruction biogeochemical fluxes: primary production of phytoplankton and remineralization increased by 7.9 % and 8.9 %, respectively, and the input of phosphates from bottom sediments by 2.1 %. As a result, winter phosphate concentrations in the photic layer increased by 12.3 % and phytoplankton biomass by 16.1 %. More precisely, the increased level of winter phosphate concentrations is explained by an imbalance between the processes of their intake and consumption: the total increase in phosphate input due to remineralization and release from bottom sediments exceeds the growth in consumption during photosynthesis, which leads to the accumulation of their winter reserves.

In contrast, scenario 3 demonstrates underestimated average values of the main ecosystem characteristics (see Table 2). This is explained by the fact that the initial conditions for the third scenario were fields obtained by adapting the modeled system to an external load equal to the long-term average. At the same time, the initial conditions for the reference scenario corresponded to adaptation to high values of external phosphorus load in the early 1980s. As a result, the total phosphorus pool in the water-bottom sediment system at the beginning of the calculations in the third scenario was lower than in the reference scenario, which led to underestimated average values of the main ecosystem characteristics.

The largest differences between the average characteristic values in scenarios 1 and 3 are for winter phosphates (17.7 %) and phosphorus release from bottom sediments (14.8 %). This is due to the fact that these indicators are primarily influenced by changes in nutrient load, rather than by an increase in water temperature, which compensates for the effects of changes in nutrient load. In the case of annual primary production and remineralization, the effects of increasing temperature are stronger, increasing the values of these characteristics. Therefore, the total decrease in average primary production and remineralization for the period under consideration is smaller than for winter phosphates and phosphorus release from bottom sediments, amounting to 6.5 % and 5.4 %, respectively.

In the third scenario, only primary production exhibits a positive trend, while the trends for winter phosphate concentrations and phytoplankton biomass are close to zero (Table 1). The lack of a trend in phytoplankton biomass changes is due to the almost complete compensation of the effects of climate-induced increases in water temperature on primary production (biomass growth) and organic matter remineralization (biomass loss). As a result, the trend in winter phosphate concentration, which, in addition to interactions with phytoplankton, is determined by phosphate inputs from bottom sediments and external sources, is also small given constant inputs from external sources. The variances of all ecosystem characteristics in scenario 3 are significantly reduced compared to scenario 1.

Thus, the absence of interannual variability in atmospheric forcing and the resulting changes in water temperature leads to relatively small changes in the trends and variance of the main characteristics of the Lake Ladoga ecosystem in the period under consideration (1980–2020). The contribution of interannual variability in atmospheric effects to the linear trends in the change in winter phosphate concentrations, summer phytoplankton biomass, and annual phytoplankton production in the photic layer in 1980–2020 is approximately 24 %, 10 %, and 21 %, respectively.

In contrast, the absence of interannual variability in external phosphorus loading is accompanied by a strong change in the trends and variance of main ecosystem characteristics (for winter phosphates and especially phytoplankton biomass, the trend virtually disappears, and for primary production, it even changes sign). In this case, relative estimates of the contributions of interannual variability in atmospheric forcing and external phosphorus loading to linear trends are meaningless due to the low values of the determination coefficient.

The calculation according to scenario 1 (see Fig. 1) clearly demonstrates a certain decrease in the main characteristics of the Lake Ladoga ecosystem in the second half of the period under consideration (1980–2020). Note that, in the absence of climate change, the rate of decline in primary production increases from 1.022 g C/ (m^2 year) (scenario 1) to 1.235 g C/ (m^2 year) (scenario 2). In scenario 3, an upward trend is observed with a rate of 0.349 g C/ (m^2 year). Thus, the decrease in phytoplankton primary production caused by a decrease in external load is partially compensated by its increase caused by climate change.

3.2. Correlations between ecosystem characteristics under climate change in atmospheric forcing and constant external nutrient loading (Scenario 3)

Phytoplankton biomass at any given time is formed as a result of several opposing biogeochemical processes. Biomass increases due to the primary production of organic matter, while it decreases due to mortality, zooplankton grazing, and gravitational sinking. All of these processes depend on both water temperature and phytoplankton concentration.

To identify correlations between the characteristics of the Lake Ladoga ecosystem under Scenario 3, a correlation matrix was calculated (Fig. 2). As can be seen from the figure, there is a strong correlation between the interannual variability of winter mineral phosphorus reserves and diatom biomass (r = 0.79), and consequently, total phytoplankton biomass (r = 0.82). However, there is no effect of winter phosphorus reserves on non-diatom biomass (r = 0.11). There is no significant relationship between the average photic layer temperature over the growing season and the biomass of total phytoplankton, diatoms, and non-diatoms.

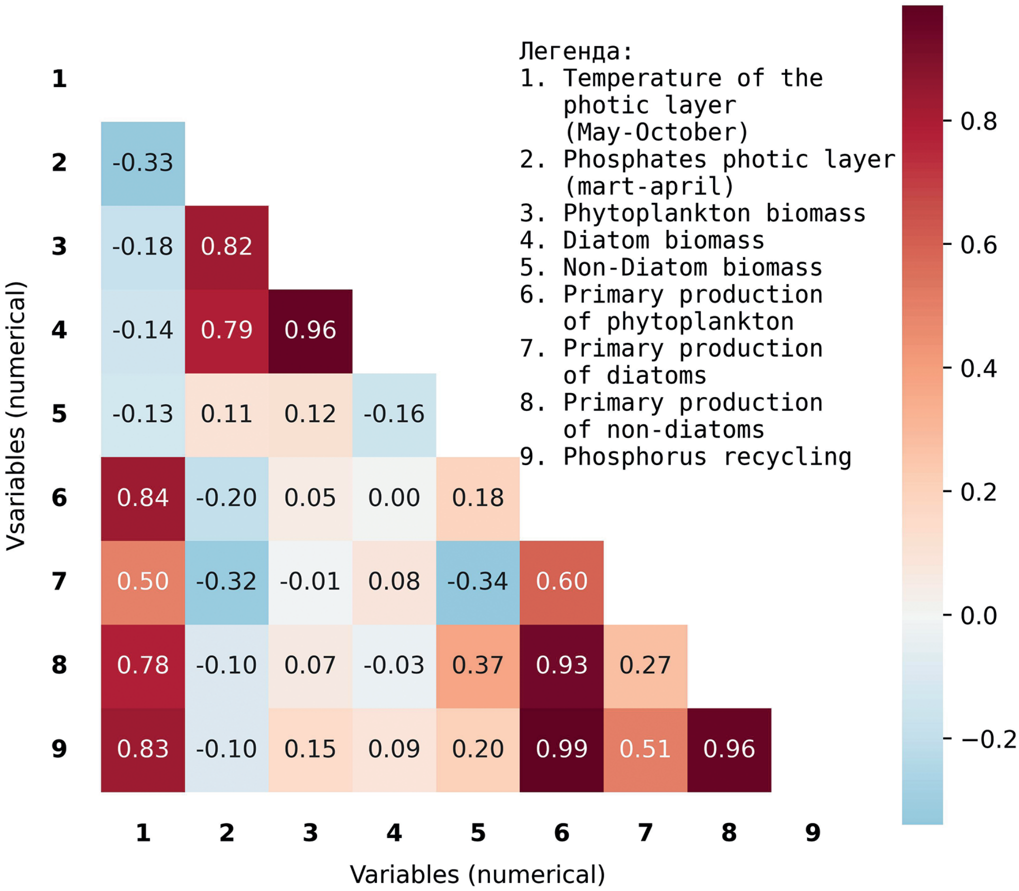

Fig. 2. Correlation matrix of Lake Ladoga ecosystem characteristics for scenario 3

At the same time, an increase in the photic layer temperature has a significant impact on the primary production of non-diatom algae (r = 0.78) and, consequently, on total primary production (r = 0.84). However, no noticeable effect of increasing temperature on diatom primary production is observed. A close relationship between variability in non-diatom primary production and the recycling process (r = 0.96), which ensures the remineralization of organic matter through zooplankton excretion and mineralization, is noted. The impact of recycling on the primary production of diatom phytoplankton is minor (r = 0.51).

Thus, the conducted analysis shows that, under conditions of constant external nutrient loading, the following main patterns are observed in the Lake Ladoga ecosystem. The level of winter phosphate reserves remains virtually unchanged, as does phytoplankton biomass. The main factor determining the level of diatom biomass is the phosphate reserve accumulated in the photic layer during the winter. Non-diatom algal blooms during the growing season are primarily supported by phosphorus turnover in the photic layer through recycling. The lack of growth in phytoplankton biomass in response to rising water temperatures is explained by the simultaneous increase in both primary production and processes causing biomass decline.

As shown above, the impact of climate change, manifested in a sustained increase in water temperature in the photic layer of Lake Ladoga, has a complex impact on ecosystem functioning. This impact is expressed not so much in a direct increase in phytoplankton biomass as in the intensification of key biogeochemical processes and matter fluxes. The most significant consequence of the observed warming is the activation of production and destruction processes, reflected in increased primary production and accelerated recycling processes.

In this regard, an analysis of the impact of climate change on the production characteristics of the main phytoplankton groups is of particular interest. Figure 3 shows the interannual dynamics of primary production of diatoms and non-diatoms over the study period. The obtained data, supplemented by calculations of statistically significant trend characteristics, demonstrate a pronounced positive trend in production processes. Under the influence of climate change, the total primary production of phytoplankton is increasing at an average rate of 0.35 g C/(m² year). Detailing this trend by individual functional groups reveals a pronounced asymmetry in contributions: the largest contribution (approximately 63 %) to the total increase is made by the increase in primary production of non-diatom algae, amounting to 0.22 g C/(m² year). The contribution of diatoms is significantly smaller – approximately 37 % of the total increase, which corresponds to an increase of 0.13 g C/(m² year).

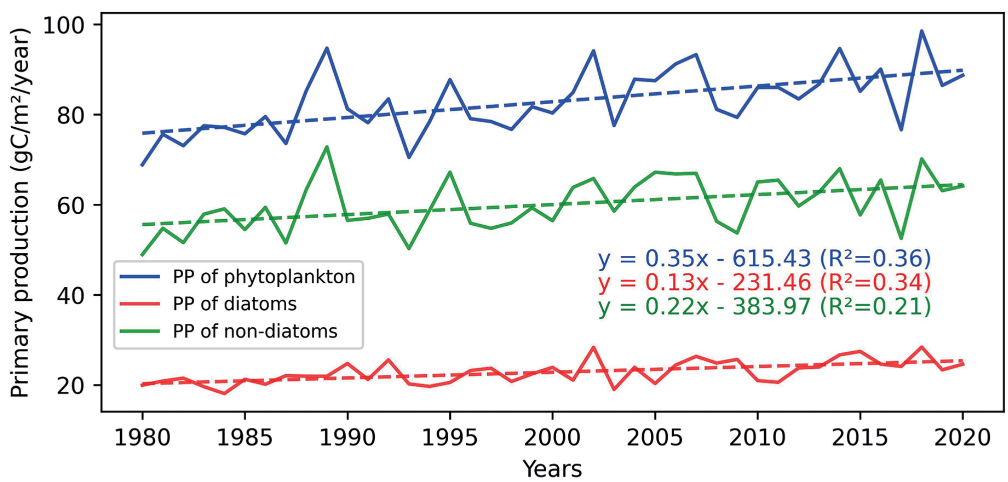

Fig. 3. Interannual dynamics of phytoplankton primary production (blue line), including diatoms (red line) and non-diatoms (green line) algae in scenario 3. The dashed line shows a linear trend

According to calculated values of the coefficient of determination (R^2), rising water temperature explains approximately 34 % of the interannual variability in non-diatom phytoplankton primary production and only 21 % of the variability in diatom production. This significant difference indicates that interannual fluctuations in weather conditions (such as changes in solar radiation intensity, wind mixing, and ice regime changes) make a significant additional contribution to the formation of annual phytoplankton primary production.

4. Concluding remarks

These numerical experiments, alternately excluding interannual variability of atmospheric forcing and external phosphorus load on Lake Ladoga, revealed the role of climate change and phosphorus load in the interannual variability of the lake's ecosystem. The results demonstrate the pronounced dominance of external nutrient load as the main factor determining the long-term dynamics of the lake's ecosystem characteristics from 1980 to 2020. The contribution of climate change to the highly deterministic linear trends in winter phosphate concentrations, summer phytoplankton biomass, and annual phytoplankton production in the photic layer amounted to only 24 %, 10 %, and 21 %, respectively. According to the calculation results, a significant decrease in these lake ecosystem characteristics occurred in the second half of the period under consideration (1980–2020). Moreover, phytoplankton production is influenced by a significant (more than 20 %) compensating effect of climate change, offsetting some of the effect of reduced nutrient load.

According to the results of an analysis of correlations between ecosystem characteristics under constant external nutrient load, non-diatom algae, which make the main contribution (63 %) to total phytoplankton production, respond strongly to climatic changes in water temperature during the period under review. Diatoms demonstrate less dependence on climate change, maintaining a close relationship with winter phosphate reserves. These estimates highlight the complex nature of the interactions between abiotic factors in regulating ecosystem productivity: water temperature effects explain only part of the observed interannual variability, yielding a significant role to other physical factors such as photosynthetically active radiation, wind regime, and ice conditions.

The approach used to identify the climatic signal under highly variable external load is of significant value for predictive assessments of the development of the Lake Ladoga ecosystem. The obtained results have important practical significance for the development of a scientifically based strategy for managing the ecological state of this unique reservoir in the context of a changing climate and anthropogenic pressure, providing a basis for making informed management decisions to preserve its natural potential.

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Conflict of interests

The authors declare no conflict of interests.

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