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Effect of Flocks of Anseriform Birds on Seston and Phytoplankton in Lakes of the Taimyr Peninsula

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Abstract—The effect of molting anseriform birds on the structure and elemental composition of phytoplankton (seston) has been assessed in 20 Arctic lakes of the Taimyr Peninsula. In lakes (part of the lake) inhabited by ~50–700 birds of six species, the average stoichiometric ratio N : P (mol : mol) was statistically significantly lower than in lakes without anseriforms: 15.8 ± 1.4 and 22.4 ± 2.7, respectively. There ~~is~~ also a tendency of higher average specific electrical conductivity in the lakes with the birds, 113 ± 32 μS/cm, when compared with those without anseriforms, 60 ± 18 μS/cm. The differences could be explained with high probability by the effect of guanotrophication, namely, by a flow in water of metabolites of molting anseriforms. The total biomass of phytoplankton and proportions of algal taxa and cyanobacteria in the total biomass ~~does~~ not differ statistically significantly in lakes with and without molting anseriforms. Therefore, under guanotrophication, the main threat of eutrophication was absent: an increase of biomass of cyanobacteria, causing the nuisance "bloom" of water. Moreover, an opposite tendency occur~~s~~: in lakes with molting anseriforms, the proportion of cyanobacteria in total biomass of phytoplankton ~~is~~ on average lower than that in lakes without the birds, 16.2 ± 5.3% and 30.8 ± 9.3%, respectively. Thus, a hypothesis ~~is~~ confirmed that artificial guanotrophication should be regarded as a suitable ecotechnology for the increase of productivity of oligotrophic Arctic lakes.

Keywords: guanotrophication, C : N : P stoichiometry, seston, phytoplankton, Taimyr, anseriform birds

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The anthropogenic eutrophication of natural water bodies—that is, the intensive input of inorganic nutrients, nitrogen, and phosphorus from wastewaters and agricultural land, causing the cyanobacterial and algal bloom, which leads to a sharp deterioration in water quality and a decrease in biodiversity—is a global environmental problem (Downing, 2014; Ibelings et al., 2016; Lurling et al., 2016; McCrackin et al., 2017; Orihel et al., 2017; Paul et al., 2022; Gubelit, 2022). Efforts are being undertaken throughout the world to combat blooming, primarily in lakes and reservoirs, for which a number of special biotechnologies (ecotechnologies) have been developed that reduce the eutrophication effect (Ibelings et al., 2016; Lurling et al., 2016; McCrackin et al., 2017; Paul et al., 2022).

However, the artificial eutrophication of Arctic lakes that are naturally oligotrophic can be used to increase fish productivity (Hyatt et al., 2004; Persson et al., 2008). Nevertheless, the artificial eutrophication of lakes that pose a risk of blooming and biodiversity loss can be ambiguously perceived by both the public and specialists taking measures to prevent eutrophication (Ibelings et al., 2016; Lurling et al., 2016; McCrackin et al., 2017; Paul et al., 2022).

Meanwhile, along with anthropogenic eutrophication, a natural process occurs that ensures the input of nitrogen and phosphorus into water bodies with the ~~vital activity products~~ of birds, called guanotrophication (Chaichana et al., 2010; Krylov et al., 2012). The consequences of guanotrophication in aquatic ecosystems may differ from those of anthropogenic eutrophication. If anthropogenic eutrophication most often leads to the toxic cyanobacterial bloom, then microalgae capable of synthesizing omega-3 long-chain polyunsaturated fatty acids (PUFA) with high nutritional value can develop during guanotrophication (Krylov et al., 2011, 2012, 2018). It is possible that bird excrements have a special stoichiometric ratio of elements C : N : P, favorable for the growth of some groups of algae (Krylov et al., 2018).

Differences that have occurred at the level of primary producers, phytoplankton, are transformed into differences at subsequent trophic levels: during guanotrophication, the proportion of copepods (Copepoda) increases in the link of consumers (zooplankton), whereas during anthropogenic eutrophication, cladocerans (Cladocera) predominate in zooplankton (Krylov et al., 2011, 2012, 2013a,b, 2018). Because, as is known, copepods have a higher PUFA content and therefore are more valuable fish food than cladocerans (Gladyshev et al., 2015), it is not surprising that accelerated growth and the development of fish is observed in the zones of guanotrophication (Stolbunov et al., 2017; Krylov et al., 2018).

Based on the data on the environmental effects of guanotrophication, we hypothesized that artificial guanotrophication (the input of fertilizers from waste products excreted by birds into the water) may be an acceptable ecotechnology to increase the productivity of oligotrophic Arctic lakes in order to accelerate their rehabilitation from accumulated damage from anthropogenic impact (Gladyshev, 2021). Also, artificial guanotrophication ~~can~~ potentially be considered an environmentally safe method of increasing the fish productivity of Arctic lakes.

The aim of this study is to determine the effect of anseriform birds on the structure and elemental composition of phytoplankton (seston) in the Arctic lakes of the Taimyr Peninsula to test the possible effects of guanotrophication by comparing the average numerical values of hydrobiological parameters in two groups of lakes: with and without molting flocks of anseriforms.

MATERIALS AND METHODS

Selection of the Study Area and Aerial Survey

This study was carried out in the lakes of Central Taimyr located in the basins of the Pyasina, Orbita, and Logata rivers, where the largest molting sites of anseriform birds not only in Taimyr, but also in Eurasia, are located. All the tundra lakes under study had similar geomorphological features: shallow, thermokarst, with intense wind mixing.

The Taimyr Peninsula is unique, because the birds using three of the four global flyways, African-Eurasian, Central, and East Asian ones, live there (Deinet et al., 2015), and it is the most important region of reproduction and molting of anseriform birds (Ebbinge et al., 2013). Not only anseriform birds nesting in the tundra of the peninsula molt on Taimyr, but also those arriving there (nonbreeding birds, or birds that lost their clutches or broods) from neighboring regions (Yamal, Gydan, the European north, and Yakutia), who spend the molting period on Taimyr.

The study area was selected based on 137 data sources containing information on the distribution and abundance of aquatic birds in more than 100 sites of the tundra zone of the Taimyr Peninsula for the period from 1928 to 2017 (http://taimyrbirds.ru/), as well as the data of our aerial surveys of 2018–2020. (Database of the Results of Aerial Surveys and Telemetry of Anseriforms of Russia. http://rggsurveys.ru/).

Anseriforms were chosen as an object of research due to the fact that, out of all groups of birds, they dwell in the lakes for the longest period and can form huge flocks in a limited water area, and they practically do not go onto land for a long time. Anseriform birds of the tribe Anserini (geese, brants, and swans) are one of the most important environmental components of Arctic ecosystems. The mass hatching of geese and brants in the study area occurs in mid-July, and even later in years with late spring (Syroechkovsky, 2013). After that, the broods stay in the nesting area sometimes until their departure, which occurs in September. During the molting period, geese, brants, and swans lose their ability to fly for a considerable period of time: from 3 to 4 weeks. Breeding and nonbreeding birds molt at different times, which determines the total duration of molting of anseriforms for a period of more than 1.5 months: from mid-July to the end of August, with the formation of huge flocks (molting sites) in limited territories. Molting birds, for protection from terrestrial predators, usually spend most of time in the water area of the lakes on the shores of which they feed (Syroechkovsky, 2013). As a rule, the molting sites are constant, since there are, in principle, few places combining a safe lake with a sufficient supply of food along the shores, and their presence largely determines the total number of geese (Rozenfeld, 2009).

Colonies of large gulls (*Larus hyperboreus* (Gunnerus, 1767) and *Larus heuglinii* (Bree, 1876)), located in the lakes, become a place of attraction for molting anseriformes, because gulls provide them with additional protection from both terrestrial and feathered predators. It should be noted that there are practically no lakes without birds in the surveyed part of Taimyr. At the height of the molting season, lakes without anseriforms, mainly lakes of glacial origin in the mountainous part of the peninsula, are visited by other species of birds (gulls and waders; falconiforms) that do not spend much time there. Waders cannot influence the composition of lake water in any way, because they do not spend a lot of time on the water and do not leave their waste products in the lake water, leaving Taimyr as early as in July–early August. As for gulls, they fly distances after the nesting period, not staying constantly on the same lakes.

According to the results of our aerial surveys conducted in 2018–2020 on the Taimyr Peninsula (with the exception of its northeastern part), 1635408 greater white-fronted geese *Anser albifrons* (Scopoli, 1769), 846810 bean geese *Anser fabalis* (Latham, 1787), 78430 red-breasted geese *Branta ruficollis* (Pallas, 1769), 6738 lesser white-fronted geese *Anser erythropus* (Linnaeus, 1758*)*, and 14 830 Bewick's swans *Cygnus columbianus bewickii* (Yarrell, 1830) are concentrated at the end of the nesting (incubation and brood rearing) and postnesting period (Database of the Results of Aerial Surveys and Telemetry of Anseriforms of Russia. http://rggsurveys.ru/).

Thus, the abundance of anseriform birds on the peninsula in summer is one of the highest in the world, and it is incomparably higher than the abundance of any other groups of birds associated with water bodies. Of the birds whose influence on the water composition is significant, only anseriforms can be considered, which remain on the water body during incubation, brood rearing, and molting, which is more than a month and a half in total.

Estimation of the Abundance and Species Composition of Birds

The search for and counting of molting birds was carried out using a Superstol seaplane with a float landing gear (the only STERKH C1 airplane); the standard flight altitude for searching for flocks of anseriform birds was 50–80 m; the survey strip width was 1600 m (800 m from each side of the airplane). Each of the surveyed lakes was also flown around the perimeter at an altitude of 20–25 m to photograph all the birds on the lake. The method of counts of flocks of anseriform birds is described in detail in the paper by S.B. Rosenfeld et al. (2017).

All the birds encountered were photographed with a Canon Mark IV camera with a 100–400 mm lens; photographs were taken from both sides of the airplane. The photo was associated both with the coordinates, with an accuracy of 0001°, and the moment bird was encountered, with an accuracy of 1 s. Swarovski 10 × 42 binoculars were used to search for the molting sites. Data processing was carried out using the Quantum GIS 3.16.5 software.

The flight tracking of the airplane and the coordinates were recorded using a Garmin GPS navigator. The counts of the number of birds and the ratios of species in flocks was carried out by direct counting of individuals in photographs. In this case, a raster grid was constructed, dividing the photos into squares. To avoid the overestimation of the number of birds, the overlap areas in the photos were determined using Photoshop CS4 (11.0.2).

A map of the study area with the sites of counts of anseriform birds and simultaneous sampling of the hydrobiological material is shown in Fig. 1. The coordinates of the studied lakes are given in Table 1. For the relatively large Lake Ayaturku, the coordinates of sampling sites in the area inhabited by birds and in the area without birds are indicated (Table 1).

The names of birds are given according to the *Checklist of the Birds of the Russian Federation* (Koblik et al., 2006).

Field Measurements and Sampling

Hydrobiological sampling and measurements of water quality parameters were carried out from a Superstol seaplane with a float landing gear (FVSP STERKH C1) in the pelagic zone of lakes from a depth of 0.3–0.5 m near the location of flocks or molting sites of birds or at some distance from the shore in their absence. The water temperature, pH, and electrical conductivity were measured with an HI98194 probe (Hanna, Germany).

The samples of phytoplankton and seston (for nitrogen and phosphorus) were taken with a 2.5-L sampler at a depth of 0.3–0.5 m into a polyethylene canister, which was transported to a field laboratory. Water samples for total carbon and nitrogen of seston were filtered through precombusted (2 h at 450°C) GF/F glass fiber filters (Whatman, Germany). The filters were dried in a desiccator with adsorbent for 24–48 h, after which they were stored in a hermetically sealed aluminum container. To determine the total phosphorus in seston, water samples were filtered through membrane filters with a pore diameter of 0.45 μm (Vladisart, Russia). The filters were dried in a desiccator with adsorbent for 24–48 h, after which they were stored in a hermetically sealed aluminum container. Water samples for phytoplankton were filtered through a Zeitz filter unit onto a membrane filter with a pore diameter of 0.45 μm until the filter pores were clogged. The filter was placed in a penicillin bottle half-filled with filtered water and fixed with 4–5 drops of fixing liquid (modified Lugol's solution).

Laboratory Analyses

To determine the carbon and nitrogen content, dried glass fiber filters with sediments were ground, placed in tin containers, and weighed. The samples were analyzed using the Flash 2000 NC Soil Analyzer (Thermo Fisher Scientific, Germany). The analyzer was calibrated prior to each series of analyses according to three values of the standard (soil sample, Thermo Scientific, United States).

The phosphorus content in seston was determined using the iCAP 6300 Duo inductively coupled plasma emission spectrometer (ICP) (Thermo Scientific, United Kingdom). Prior to analysis, the samples were dried to a constant weight; then they were reduced to ash in a mixture of chloric and nitric acids (in a ratio of 1 : 1). The mineralized precipitate was transferred to polypropylene tubes and diluted with deionized water (18 MΩ) to 10 mL. Simultaneously with the samples, a blank sample was prepared, and the filter from the same batch onto which the seston samples were filtered was ashed. The spectrometer was calibrated using the phosphorus standard (P, CGP10) for ICP spectrometry (Inorganic ventures, United States). Scandium (Sc, 5 mg/L) was used as an internal standard (Scandium standard for ICP, Fluka, Switzer-

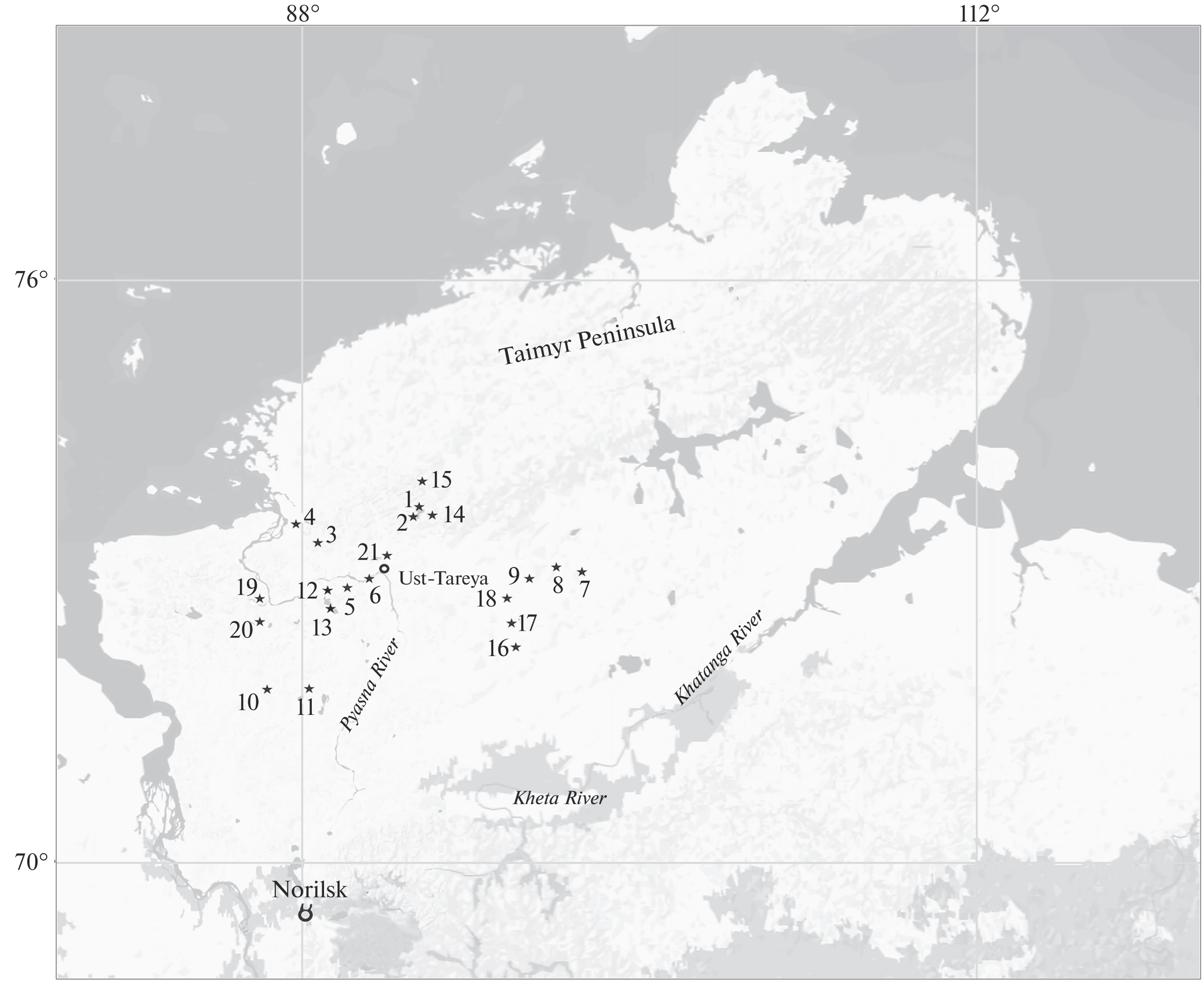

Fig. 1. Map of the studied lakes of the Taimyr Peninsula, 2022: (*1, 2*) Ayaturku (sampling sites in the northern and southern parts of the lake), (*3*) Dyagonde, (*4*) Bezymyannoe 1, (*5*) Dyuikhoka, (*6*) Bezymyannoe 2, (*7*) Satubalaturku, (*8*) Bezymyannoe 3, (*9*) Bezymyannoe 4, (*10*) Bezymyannoe 5, (*11*) Bezymyannoe 6, (*12*) Bezymyannoe 7, (*13*) Khelaliturku, (*14*) Bezymyannoe 8, (*15*) Bezymyannoe 9, (*16*) Bezymyannoe 10, (*17*) Bezymyannoe 11, (*18*) Bezymyannoe 12, (*19*) Dyalidaramu, (*20*) Bezymyannoe 13, and (*21*) Bezymyannoe 14.

land). Deionized water (18 MΩ) was used in the preparation of calibration standards and dilution of samples. Concentrated hydrochloric acid (1 : 100) was added to the standards.

The species composition and abundance of phytoplankton were determined under a microscope in a Fuchs–Rosenthal chamber with a volume of 3.2 μL. Cell sizes were determined using an eyepiece micrometer. Biomass was estimated from cell volume, equaling the specific mass to one (*Rukovodstvo po gidrobiologicheskomu monitoringu* ..., 1992).

Statistical Processing

In the statistical analysis, all lakes were divided into two groups: with molting anseriform birds and without birds. Thus, according to the aim of the study, the differences between these two groups (i.e., the presence or absence of bird influence) were determined against the background of the inevitable variability of hydrochemical and hydrobiological parameters within groups of lakes, as well as the differences in the number of birds inhabiting them. The Kolmogorov–Smirnov test was used to check whether the data were normally distributed. Student's test was used to compare the means in independent samples with a normal distribution. Calculations were performed using the STATISTICA 9.0 software package (StatSoft, United States).

RESULTS

The following species of anseriform birds were found in the surveyed lakes: bean geese, red-breasted

Table 1. Characteristics of the lakes of the Taimyr Peninsula under study (2022): lake area (S, km^2), presence/absence of molting anseriform birds (+/–), water temperature (T, °C), pH, and electrical conductivity (EC, μS/cm)

Lake	Coordinates	S	Date	Birds	T	pH	EC
Ayaturku (north)	73°52′ N 92°09′ E	79.5	23 Jul	+	9.2	8.0	138
Ayaturku (south)	73°49′ N 91°53′ E		23 Jul	–	7.3	8.4	194
Dyagonde	73°31′ N 88°33′ E	2.7	25 Jul	–	8.8	7.7	81
Bezymyannoe 1	73°43′ N 87°42′ E	0.2	25 Jul	+	14.0	6.3	42
Dyuikhoka	73°05′ N 89°33′ E	3.3	26 Jul	–	11.4	7.6	64
Bezymyannoe 2	73°10′ N 90°19′ E	0.5	26 Jul	–	13.7	7.5	23
Satubalaturku	73°15′ N 97°38′ E	2.2	27 Jul	–	13.3	7.8	41
Bezymyannoe 3	73°17′ N 96°45′ E	0.3	27 Jul	+	14.8	8.4	120
Bezymyannoe 4	73°10′ N 95°50′ E	0.3	27 Jul	–	15.4	7.9	40
Bezymyannoe 5	72°02′ N 88°14′ E	0.7	28 Jul	–	16.2	7.5	24
Bezymyannoe 6	72°02′ N 86°48′ E	0.5	28 Jul	+	15.9	8.4	54
Bezymyannoe 7	73°03′ N 88°53′ E	0.7	3 Aug	+	9.7	8.1	102
Khelaliturku	72°52′ N 88°58′1 E	44.0	3 Aug	–	10.2	7.2	36
Bezymyannoe 8	73°50′ N 92°18′ E	0.6	5 Aug	+	12.4	8.7	377
Bezymyannoe 9	74°05′ N 92°10′ E	0.6	5 Aug	+	9.3	8.6	290
Bezymyannoe 10	72°29′ N 95°22′ E	0.5	7 Aug	+	14.7	7.7	33
Bezymyannoe 11	72°43′ N 95°14′ E	0.8	7 Aug	–	14.3	8.3	40
Bezymyannoe 12	72°59′ N 95°03′ E	0.6	7 Aug	+	14.2	8.1	41
Dyalidaramu	72°58′ N 86°33′ E	3.8	13 Aug	+	11.6	7.6	61
Bezymyannoe 13	72°44′ N 86°33′ E	0.8	13 Aug	+	12.0	7.5	42
Bezymyannoe 14	73°21′ N 90°49′ E	0.8	14 Aug	+	13.1	7.5	52

geese, greater white-fronted geese, the long-tailed duck *Clangula hyemalis* (Linnaeus, 1758), the greater scaup *Aythya marila* (Linnaeus, 1761), and Bewick's swan. The number and species composition of birds in the studied lakes are shown in Table 2.

The water temperature, pH, and electrical conductivity (EC) in lakes with and without anseriform birds (Table 1), on average, did not differ significantly according to the Student's test ($p > 0.05$). However, it should be noted that there is a tendency for a higher average EC value in lakes with birds, 113 ± 32 μS/cm, when compared with lakes without birds, 60 ± 18 μS/cm.

The content of elements in seston and C : N and C : P stoichiometric ratios in lakes with birds and without birds on average did not differ significantly (Table 3). However, the average ratio of N : P in lakes with birds turned out to be significantly lower than in lakes without birds (Table 3).

The biomass and species composition of the dominants and subdominants of phytoplankton are shown in Table 4. The total biomass of phytoplankton and the proportion of algae and cyanobacteria in the total biomass in lakes with and without birds on average did not differ statistically significantly (Table 5). However, a higher average proportion of Cyanobacteria in lakes without birds and a higher average proportion of green algae (Chlorophyta) in lakes with birds should be noted as a trend (Table 5).

DISCUSSION

Out of all the anseriforms found in large numbers in the course of the surveys, bean geese and greater white-fronted geese constituted the major proportion. Geese and brants feed mainly on terrestrial plants (Rozenfeld, 2009). Bewick's swans also feed a lot on the water, foraging for aquatic plants, and possibly aquatic invertebrates (Popovkina and Rozenfeld, 2012). The gastrointestinal tract in geese and swans is arranged in such a way that they have to carry large volumes of plant mass through it, since these birds do not have cellulose-splitting symbionts (Sedinger, 1986; Kondratiev, 2008). Defecation occurs at least once every 5 min. Geese secrete feces not only on land, but also in water, especially during molting (Van Geest et al., 2007). The long-tailed duck and greater scaup found on one of the lakes, together with greater white-fronted geese, feed on aquatic invertebrates (*Polevoy opredelitel* ..., 2011).

Thus, according to the classification proposed for aquatic birds in relation to their participation in the nutrient cycle (Boros, 2021), most of the detected species belong to the net-importer guild. The relatively small number of long-tailed ducks and greater scaups represent the net-exporter guild, and Bewick's swans represent the importer–exporter guild (Boros, 2021). That is, most of the birds found on the studied lakes provided cycling of nutrients and mineral elements, including nitrogen and phosphorus from land to water.

Table 2. Abundance of molting anseriform birds on the lakes of the Taimyr Peninsula under study in 2022

Lake	Species of birds	Number of individuals
Ayaturku (north)	Bean geese	511
	Red-breasted geese	16
Ayaturku (south)		0
Dyagonde		0
Bezymyannoe 1	Red-breasted geese	554
	Bean geese	85
Dyuikhoka		0
Bezymyannoe 2		0
Satubalaturku		0
Bezymyannoe 3	Bean geese	42
	Greater white-fronted geese	20
Bezymyannoe 4		0
Bezymyannoe 5		0
Bezymyannoe 6	Greater white-fronted geese	64
	Bean geese	80
Bezymyannoe 7	Bean geese	206
Khelaliturku		0
Bezymyannoe 8	Bean geese	209
Bezymyannoe 9	Bean geese	53
Bezymyannoe 10	Greater white-fronted geese	62
	Pintail	4
	Long-tailed duck	65
	Greater scaup	21
Bezymyannoe 11		0
Bezymyannoe 12	Greater white-fronted geese	58
Dyalidaramu	Bean geese	216
Bezymyannoe 13	Bean geese	107
Bezymyannoe 14	Greater white-fronted geese	112
	Bewick's swan	61

Table 3. Average (± standard error; n is the number of samples) content of elements in seston (mg/L) and their stoichiometric ratios (mol : mol) in the lakes of the Taimyr peninsula inhabited by anseriform birds and those without birds in July–August 2022; t is the statistical significance of differences according to the Student's test; statistically significant differences ($p < 0.05$) are in bold

Elements	With molting anseriform birds ($n = 12$)	Without anseriform birds ($n = 9$)	t
C	0.62 ± 0.18	0.80 ± 0.25	0.58
N	0.08 ± 0.03	0.11 ± 0.04	0.47
P	0.012 ± 0.003	0.013 ± 0.004	0.07
C : N	8.0 ± 0.2	7.9 ± 0.3	0.27
C : P	132.6 ± 12.2	162.8 ± 18.4	1.37
N : P	15.8 ± 1.4	22.4 ± 2.7	**2.22**

The fluxes of nutrients and elements resulting from the vital activity of molting anseriforms were probably the reason for the differences found in the seston and phytoplankton of the studied lakes. First and foremost, it is necessary to note statistically significant differences in the stoichiometric ratio N : P, which was on average almost one and a half times lower in lakes inhabited by birds. Our results are consistent with the data of other authors, according to which phosphorus enters the water with the feces of geese in a greater proportion than nitrogen, when compared with the proportions of these elements in the surface runoff (Dessborn et al., 2016). The stoichiometric ratio of nitrogen and phosphorus in the feces of geese from Danish wetlands, calculated according to Hahn et al. (2008), was 16.2 mole : mole; that is, it turned out to be almost similar to the average value N : P = 15.8, recorded by us for the seston of the lakes inhabited by birds. In the water of experimental microcosms, in which the ~~products of the vital activity~~ of birds were added, the ratio of total nitrogen and phosphorus calculated according to the data of Krylov et al. (2013b) was 14.5 mol : mol, whereas in the control this ratio was 38.4 mol : mol, which is consistent with our data on the seston of the studied lakes with and without birds.

Along with a significantly lower average stoichiometric ratio of N : P in seston and the tendency of a lower C : P ratio, in lakes with molting anseriform birds, a tendency of a higher average value of electrical conductivity (EC) was found, indicating a higher concentration of dissolved salts. The latter trend may be of significant importance for phytoplankton, since it has been experimentally established that in Arctic lakes its increase is limited not only by a low content of nitrogen and phosphorus, but also by some trace elements (Van Geest et al., 2007), probably contained in bird waste products.

Unlike the detected qualitative hydrochemical differences, the quantity of phytoplankton in lakes with molting anseriform birds and without birds on average did not differ significantly. A similar phenomenon was observed by other authors in the Arctic lakes of Spitsbergen: the concentration of phytoplankton chlorophyll did not correlate with an increase in nitrogen and phosphorus concentrations in the water under the influence of geese (Van Geest et al., 2007). The authors explained the absence of an increase in the phytoplankton biomass by the fact that the number of primary consumers, daphnia intensively grazing on phytoplankton, increased in the lakes (Van Geest et al., 2007). That is, presumably, all additional phytoplankton production formed due to additional inorganic nutrients entering from birds transited to the next trophic level (Van Geest et al., 2007). Thus, measurements of the production of phytoplankton and zooplankton in the Arctic lakes affected by the ~~vital activity products~~ of molting anseriform birds is an urgent task for future research.

Table 4. Total biomass (B, μg/L) and species composition of dominants and subdominants (% of total biomass) of phytoplankton in lakes with molting anseriform birds (+) and without anseriform birds (–); Taimyr Peninsula, 2022

Lake	Birds	B	Dominant (%)	Subdominant (%)
Ayaturku (north)	+	249	*Dinobryon cylindricum* (37.9)	*Dinobryon divergens* (19.6)
Ayaturky (south)	–	181	*Dinobryon sociale* (57.5)	*Trachellomonas* sp. (9.0)
Dyagonde	–	383	*Melosira islandica* (54.5)	*Melosira italica* (24.0)
Bezymyannoe 1	+	139	*Dinobryon cylindricum* (27.5)	Chlorococcales (18.0)
Dyuikhoka	–	113	*Dinobryon divergens* (45.6)	*Trachellomonas* sp. (10.1)
Bezymyannoe 2	–	561	*Aphanizomenon flos-aquae* (34.4)	*Gyrosigma acuminatum* (26.7)
Satubalaturku	–	563	*Anabaena* sp. (35.4)	*Dinobryon bavaricum* (25.1)
Bezymyannoe 3	+	66	*Navicula* sp. (34.1)	Centricae (25.7)
Bezymyannoe 4	–	321	*Anabaena* sp. (25.1)	*Asterionella formosa* (16.8)
Bezymyannoe 5	–	2120	*Anabaena* sp. (58.2)	*Aphanizomenon flos-aquae* (7.9)
Bezymyannoe 6	+	1292	*Anabaena* sp. (43.4)	*Melosira italica* (20.5)
Bezymyannoe 7	+	277	*Synedra acus* (28.7)	*Melosira* sp. (17.8)
Khelaliturku	–	205	*Surirella biseriata* (53.3)	*Anabaena* sp. (15.5)
Bezymyannoe 8	+	109	*Cosmarium formulosum* (65.5)	*Gomphonema acuminatum* (15.9)
Bezymyannoe 9	+	185	Centricae (63.6)	*Peridinium* sp. (23.3)
Bezymyannoe 10	+	2238	*Anabaena* sp. (32.1)	*Staurodesmus subtriangularis* (19.2)
Bezymyannoe 11	–	2074	*Anabaena* sp. (61.5)	*Cosmarium* sp. (7.6)
Bezymyannoe 12	+	1294	*Anabaena* sp. (21.7)	*Staurastrum* sp. (19.5)
Dyalidaramu	+	243	*Cymatopleura solea* (25.3)	Centricae (22.5)
Bezymyannoe 13	+	159	*Anabaena* sp. (21.2)	Centricae (20.2)
Bezymyannoe 14	+	1317	*Anabaena* sp. (37.1)	*Dinobryon* sp. (24.9)

The taxonomic composition of phytoplankton in lakes with molting anseriform birds and without birds did not differ significantly. That is, the main threat of eutrophication, an increase in the cyanobacterial biomass leading to the water bloom, was absent. Moreover, the opposite trend was found: in lakes with birds, the proportion of cyanobacteria in the phytoplankton biomass was on average lower, and the proportion of diatoms (Bacillariophytes) and green (Chlorophyta) and dinophytic (Dinophyta) algae was higher than in the lakes without birds. An increase in the proportion of dinophytic algae under the influence of birds was also observed by other authors (Krylov et al., 2012, 2018). Algae are known to be a more valuable food for the consumers than cyanobacteria, including due to a more favorable stoichiometric ratio of elements and the composition of fatty acids (Gulati and DeMott, 1997). In general, our data confirmed the existing understanding of higher nutritional value of phytoplankton and seston for consumers when bird waste products enter lakes (Krylov et al., 2012, 2018; Vizzini et al., 2016).

It should be noted that, in lakes and reservoirs of the middle latitudes, in some cases, the proportion of cyanobacteria increases and the proportion of diatoms decreases as a result of the effect of birds belonging to other orders than anseriformes (Krylov et al., 2011). In fact, gulls, herons, pelicans, cormorants, and some other birds, mainly carnivorous (fish-eating) and omnivorous, can increase eutrophication, leading to a cyanobacteria bloom in water bodies of middle and low latitudes (Martín-Vélez et al., 2019; Verstijnen et al., 2021). It is not excluded that the differences may be caused by the different composition of the secreted metabolites of herbivorous and carnivorous birds. It is considered that carnivorous birds excrete significantly more nitrogen and phosphorus than herbivores (Hahn

Table 5. Average (± standard error; *n* is the number of samples) biomass of phytoplankton (B, μg/L) and the proportion of divisions in the biomass (%) in the lakes of the Taimyr Peninsula inhabited by anseriform birds and without anseriform birds in July–August 2022; *t* is the statistical significance of differences according to the Student's test

Phytoplankton	With molting anseriform birds ($n = 12$)	Without anseriform birds ($n = 9$)	t
Biomass	630 ± 206	725 ± 265	0.28
Cyanobacteria	16.2 ± 5.3	30.8 ± 9.3	1.36
Bacillariophyta	37.0 ± 8.0	33.2 ± 10.3	0.29
Chlorophyta	21.5 ± 7.1	9.2 ± 2.4	1.63
Chrysophyta	21.8 ± 7.1	23.1 ± 9.1	0.11
Dinophyta	2.6 ± 2.2	1.1 ± 0.1	0.67

et al., 2007). It is also possible that birds of different species belong to different guilds of importers and exporters (Mukherjee and Borad, 2001; Boros, 2021).

In general, according to available data, in desert regions with poor soils and glaciers, the contribution of anseriform birds to allochthonous nitrogen and phosphorus fluxes can be very significant (Manny et al., 1994; Dessborn et al., 2016). Our data are consistent with the ideas about the significant contribution of anseriform birds to the functioning of aquatic ecosystems of Arctic water bodies located in the tundra.

CONCLUSIONS

In the Arctic lakes located in the tundra of the Taimyr peninsula inhabited by anseriform birds, differences in stoichiometric ratios of inorganic nutrients in seston compared to those in lakes without birds, as well as higher values of specific electrical conductivity, were found. The observed changes can, with high probability, be explained by the effect of guanotrophication, namely, the entry of the ~~vital activity products~~ of molting anseriforms into water. The taxonomic composition of phytoplankton in lakes with and without birds did not differ statistically significantly. The taxonomic composition of phytoplankton in lakes with and without birds did not differ significantly. That is, during guanotrophication, there is no threat of eutrophication, because the cyanobacterial biomass leading to harmful water bloom does not increase. Moreover, the opposite trend was found: the proportion of cyanobacteria in phytoplankton biomass was on average lower, and the proportion of microalgae (Bacillariophyta, Chlorophyta, and Dinophyta) in lakes with molting anseriform birds was higher than in lakes without birds. In general, our data confirmed the existing understanding of the higher nutritional value of phytoplankton (seston) for consumers when birds' ~~vital activity products~~ enter the lakes. Thus, the hypothesis was confirmed that artificial guanotrophication could potentially be considered an acceptable ecotechnology to increase the productivity of oligotrophic Arctic lakes.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interests. The authors declare that they have no conflict of interest.

Statement on the welfare of animals. All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

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