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Article

The influence of moose (*Alces alces* L., 1758) rumen chyme on soil eutrophication in ecosystems of the southern taiga

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Abstract. The influence of the piles of winter rumen digesta (chyme) from moose (*Alces alces*) on soils in natural sites is discussed. In early May 2020, the piles of chyme (5 kg each) were placed in three habitats (forest, deforestation area, overgrown field). The analysis of nutrients in soil was made after four months (in September). It has been established that in the process of leaching liquid components of chyme and decomposition of its plant residues, the pH in soil increases to the level of neutrality. The concentration of nitrate nitrogen in the soil under chyme piles is several times higher than the control values, averaging 14.8–18.6 mg/kg, depending on the habitat. The amount of ammonia nitrogen is three times higher in the experiment plots than in the natural sites of the forest. In the field and deforestation area, the differences between chyme and control plots are insignificant. In the upper soil layer, the quantity of phosphates under chyme influence is 6.0–25.0 times higher than in intact habitats. The difference in the concentration of mobile forms of potassium between the control and experimental plots with chyme is 2.1–8.0 times in the upper soil layers of different ecosystems. The ratio of nitrate and ammonium nitrogen to phosphates in the soil under chyme piles varies depending on the soil layer and habitat from 1:4.8 to 1:19.4; in the control sites, this ratio is from 1:0.8 to 1:2.9. The ratio of mineral nitrogen to mobile potassium in the soil under chyme is 1:10.7 – 1:21.5, and in the control – from 1:2.1 to 1:7.8. The possibilities to use the moose chyme as a potential source of fertilizers in hunting grounds of the taiga zone are being discussed.

Keywords: rumen chyme, wild ungulates, chemical composition of soil, taiga ecosystem

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Научная статья

Влияние химуса из рубца европейского лося (*Alces alces* L., 1758) на эвтрофикацию почв в экосистемах южной тайги

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Аннотация. Представлены результаты по содержанию питательных веществ в почве в местах выкладки куч содержимого рубца (химуса) от добытых в зимний период лосей (*Alces alces*). Кучи химуса (по 5 кг) размещали в начале мая 2020 г. в трех биотопах (лес, вырубка, зарастающее поле). Анализ питательных веществ в почве проводили через 4 месяца (в сентябре). Установлено, что в процессе выщелачивания растительных остатков химуса происходит повышение уровня pH в почве до уровня нейтральности. Концентрация нитратного азота в почве под кучами химуса в несколько раз превышала контрольные показатели, составляя в среднем 14.8–18.6 мг/кг в зависимости от биотопа. Содержание аммонийного азота было в 3 раза выше природного фона в лесу; в поле и на вырубке эти отличия были слабо выражены. В верхнем горизонте почвы содержание подвижных фосфатов было в 6.0–25.0 раза выше, чем в интактных биотопах. Разница в концентрации подвижного калия между контрольными образцами почв и участками с химусом лося в верхнем горизонте почвы отличалась в разных биотопах в 2.1–8.0 раза. Соотношение нитратного и аммонийного азота к подвижным фосфатам в почве под кучами химуса варьировало в зависимости от горизонта почвы и биотопа от 1 : 4.8 до 1 : 19.4, а на контрольных участках это соотношение изменялось от 1 : 0.8 до 1 : 2.9. Отношение минерального азота к подвижному калию в почве на участках под химусом варьирует от 1 : 10.7 до 1 : 21.5, а в контроле – от 1 : 2.1 до 1 : 7.8. Обсуждаются возможности использования химуса лося в качестве потенциального источника удобрений в охотничьих угодьях таежной зоны.

Ключевые слова: содержимое рубца, дикие копытные, химический состав почвы, таежная экосистема

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Introduction

The moose (*Alces alces* L., 1758) is one of the most well-studied taiga herbivorous mammals. In recent decades, various aspects of its participation in biogeochemical processes in ecosystems have been covered in detail (Bowyer et al., 1997; Christenson, 2010; Leroux et al., 2020; Pastor et al., 1993; Razgulin, 2022; Swain et al., 2023).

Moose hunting is a popular and sought-after activity in many grounds in Russia. According to official statistics, about 40–50 thousand individuals of this ungulate have been harvested annually in the country in recent years (Kolesnikov et al., 2022). After harvesting, the moose carcass must be processed within 3–4 hours (Yazan, 1961), so hunters often butcher ungulates directly in the wild. Humans do not use all parts of these animals. Hunters often leave large amounts of biological waste in natural ecosystems after cutting up carcasses. Animal organic matter is quickly taken apart and utilized by predators and scavengers (Barton and Bump, 2019; Lyabzina et al., 2019; Selva et al., 2019). There is another situation with the contents of the gastrointestinal tract of moose, which is a mixture of plant particles, digestive enzymes, and microorganisms.

Ungulate droppings consist mainly of plant components and decompose rather slowly in both taiga and tundra ecosystems. The long process of dropping decomposition has been noted even in warm climates, and fecal contamination limits the use of pastures and deters herbivores from these territories (Crowder, 1985). Nevertheless, solid feces of herbivorous mammals affect biogeochemical flows in the ecosystem, in particular, they affect the chemical composition of soils, enriching them with various elements (Bowyer et al., 1997; Hobbs, 1996; Pastor et al., 1993). Herbivore feces promote a rapid nutrient cycle in the ecosystem, in contrast to a slow cycle maintained by the usual decomposition of plant fragments from the litter (Bakker et al., 2004; Christenson, 2010). A large amount of nutrients (especially nitrogen) is returned to soil with dung (Jarvis, 2000). However, the chemical composition of herbivore feces varies greatly depending on the animal species and its diet (Valdes-Correcher et al., 2019).

The stomach contents of ungulates, or chyme, are much more enriched with nutrients. The composition of chyme includes a variety of microorganisms, enzymes, and biologically active compounds (Adetunji et al., 2022; Van Soest, 1994) that makes it more attractive to organic matter decomposers in the soil. However, there is no information on the impact of this type of biological waste on various components of ecosystems. The role of various animal carcass remains in maintaining biodiversity and sustainability of taiga ecosystems is largely unknown, therefore, the research in this topic is relevant within the framework of the rational use of wild ungulate resources.

The aim of this study was to assess the influence of moose chyme on the concentration of nutrients in soils of various taiga ecosystems.

Material and methods

In 2020, the research was conducted in the scientific and experimental hunting farm of the Zhitkov Russian Institute of Game Management and Fur Farming (Kirov region, Zuevsky district, 1.0–1.5 km from the Motous village (N 58°30' E 50°50') located in the southern taiga.

Three key biotopes were selected as experimental sites: an overgrown field, a deforestation site, and a mixed forest. Moose habitats, which have woody and shrubby vegetation, represent different types of forest hunting grounds (Kozlovsky, 1971). The granulometric composition of soils in experimental plots was determined according to GOST 12536-2014[1].

1) The overgrown field is an area previously used for haymaking, sowing, and grazing of small domestic ungulates. Currently, these are mosaic lands where patches of forb communities alternate with areas of woody and shrubby vegetation (*Betula* sp., *Salix* sp. and *Pinus sylvestris* up to 5–7 m high and up to 20 years old). The projective cover of trees and shrubs is 20-40%. The dominant soil type is transformed illuvial-ferruginous sandy and sandy-loam podzol (umbric podzol) underlain by loams at depths from 0.5 to 1.0 m. The basis of the soil granulometric composition is made up of particles of 0.25–0.5 mm (50.8–52.8% in the upper layer (0–5 cm) and 59.7–62.8% in the lower (5–20 cm) and 0.10–0.25 mm (34.4–39.9% in the upper layer and 23.3–27.4% in the lower layer). Unlike other biotopes, the lower soil layer contains pebbles and soil particles larger than 10 mm (2%).

2) The 10-year-old deforestation site has been formed on the place of a mixed spruce-pine forest. *Populus tremula*, *Betula pendula*, *B. pubescens*, *Salix caprea* up to 3.5 m high and certain *Picea obovata* trees grow here. The total projective cover of undergrowth and shrubs reaches 90–95%. The grass cover is 30-50% (on average). The soil is a highly transformed illuvial-ferruginous sandy and sandy-loam podzol with a good leaching regime without clearly visible litter and without distinctly differentiated boundaries between soil horizons. The basis of this homogeneous soil is made up of approximately equal proportions of 0.25–0.5 mm particles (49.2% in the upper layer and 35% in the lower layer) and 0.10–0.25 mm particles (46.0% in the upper layer, 57.9% in the lower layer).

3) The site of old mixed pine-spruce forest with birch. The age of *Pinus sylvestris* trees is up to 120 years. The cover of the tree layer is 80–90%, shrubs – 20–40%, dwarf shrubs (dominated by *Vaccinium myrtillus*), forbs and grasses cover 40–60%. The soil is a typical illuvial-ferruginous podzol with a thick litter (5–8 cm), coarse-textured humus horizon (3–4 cm) and eluvial horizon (10–15 cm). The soil particles of 0.25–0.5 mm (71.5%) and 0.10–0.25 mm (19.5%) dominate in the upper soil layer. The proportion of large particles in the lower soil layer is smaller: 0.25–0.5 mm (54.7–58.8%) and 0.10–0.25 mm (35.9–38.7%).

It has been known that the increase in soil fertility due to adding manure to it in late autumn and winter does not differ from that when adding manure in the spring since due to low temperatures and permafrost of the soil, the loss of nitrogen and other nutrients is insignificant (Randall and Goss, 2008). For this reason the spring period was chosen as the beginning of our experiment with adding moose chyme to the soil surface.

In March 2020, the samples of moose rumen contents (from males and females aged 1 to 4 years) were collected. The animals were harvested under official permits in accordance with the state scientific program "Monitoring of biological resources of hunting industry and factors determining their condition to ensure sustainable nature management" (No. 0766-2019-0001). The samples of fresh chyme were frozen and stored at −20 °C until the start of experimental study in the wild.

The collected moose chyme samples were determined for nitrogen content according to Kjeldahl method (GOST 13496.4-93)[2] and phosphorus by the photometric method (GOST 26657-97)[3]. Potassium was not determined in the rumen contents.

For the experiment, the mixed homogeneous mass of the chyme from different moose individuals was obtained. In early May, 5 kg portions of rumen contents were laid out in a single pile on the soil surface in different biotopes in triplicate (Fig. 1). The chyme mass of 5 kg was calculated experimentally. Each chyme pile in the experiment was placed on an area of 0.5 m^2 corresponding to the placing of 20 kg of chyme from one adult moose on an area of 2 m^2 (equivalent to 100 t/ha). This level refers to extreme values of a single dose of organic matter (fresh manure) introduced into soil (Semenov et al., 2023).

[1] GOST 12536-2014. Soils. Methods of laboratory determination of granulometric (grain) and microaggregate composition.

[2] GOST 13496.4-93. Feed, mixed feed, feed raw materials. Methods for determination of nitrogen and crude protein.

[3] GOST 26657-97. Feed, mixed feed, feed raw materials. Methods for determining phosphorus.

A gradual, directed vertical change in the chemical composition of the soil profile occurs due to the infiltration of liquid components of the chyme. The horizontal migration of nutrients from fertilizers is insignificant in the soils of taiga ecosystems (Beznosikov, 2001).

In mid-September (after 4 months), 6 soil samples were taken in each of the experimental sites: 3 experimental soil samples under the spring chyme piles and 3 control soil samples – at a distance of 3 m from each experimental site with similar characteristics. It was done to exclude the factors that influence the chemical composition of soil as microrelief and features of the mosaic vegetation structure (Fedorets et al., 2006; Karpachevsky, 1977). Additionally, the need to collect control samples is also due to the fact that the maximum indicators of nutrient accumulation in soil are observed due to the influx of fresh litter in the autumn (Fedorets and Bakhmet, 2003), and without control samples it is impossible to separate the effect of the chyme nutrients from other natural nutrients.

After removing the litter, the soil samples were collected from two layers (0–5 cm and 5–20 cm). A soil sample of up to 500 g was taken from each layer. The choice of these layers is sufficient for the analysis, since it is known that when nitrogen fertilizers are applied in the taiga ecosystems, nitrogen is usually concentrated no deeper than 40 cm (Beznosikov, 2001). These horizons are most fully used by plant roots (Orlov, 1991) and here the closest connection is observed between the biogeocenotic field and soil properties (Karpachevsky, 2005).

In accordance with the accepted approach (Arinushkina, 1970), the standard parameters defining the nutrient regime of soils were determined in the samples: pH, P_2O_5, K_2O, NH_4+-N, N-NO_3^-. The indicator pH (salt extract) was measured according to GOST 26483-85[4]. Mobile phosphorus (P_2O_5) and potassium (K_2O) were extracted from soil with the HCl solution (0.2 mol/dm^3) and their concentration was estimated by a photoelectrocolorimeter (GOST R 54650-2011)[5]. Ammonium nitrogen (NH_4+-N) was determined using a photoelectrocolorimeter (GOST 26489-85)[6]. Nitrate nitrogen (N-NO_3^-) was analyzed by an ion-selective electrode (GOST 26951-86)[7].

Results

In winter, moose are browsing mainly on trees and shrubs that have a low concentration of nutrients (Dunin and Kozlo, 1992; Filonov, 1983; Veber et al., 1992). In different moose individuals, we determined a fairly similar concentration of nitrogen in the winter rumen contents - 17.18 ± 0.37 g/kg, and phosphorus – 10.72 ± 0.43 g/kg of absolute dry weight. This allows us to speak about similar state of the chemical composition of the chyme in herbivores living in the same areas of hunting grounds. The mass fraction of moisture in air-dried samples was 8.1 ± 0.1%. The moisture of the rumen contents was 81.7% (on average, n = 75). Thus, 1 kg of raw moose chyme in the experiment contained 2.9 g of nitrogen and 1.8 g of phosphorus.

Four months after the chyme was laid out, the increase in the soil pH level was noted in all biotopes (Fig. 2). A very high pH was observed in the overgrown field. Here, the average pH was 6.50 ± 0.15 in the upper soil layer. The minimum excess of pH compared to the control samples was registered in the deforestation area, where the average pH in the upper layer was 3.73 ± 0.22. A higher pH level was found in the upper soil layers compared to the underlying layers in all experimental sites. At the control plots, the pH did not exceed 5.6 in the overgrown field, 3.7 in the forest, and 3.8 in the deforestation site. The difference in pH level between the experimental and control samples in the upper soil layer was 1.07 ± 0.55 in the forest, 1.00 ± 0.21 in the field, 0.23 ± 0.13 in the deforestation site, and in the lower layer this difference was lower – 0.47 ± 0.22, 0.63 ± 0.20, 0.50 ± 0.30, respectively.

The NH_4^+-N quantity in the experiment exceeds the control samples (on average, 3 times) only in the forest because the limited movement of chyme infiltrates in the soil profile due to the thick litter and dense system of plant roots, which help to retain chyme particles in the upper soil horizon. The maximum concentration of NH_4^+-N in the upper layer of the forest site was 113.7 mg/kg. The excess of ammonium nitrogen in the chyme sites was insignificant in the overgrown field and in the deforestation area if compared with the control plots. In general, when pairwise comparing samples for both analyzed

[4] GOST 26483-85. Soils. Determination of pH of salt extract, exchangeable acidity, exchangeable cations, nitrate content, exchangeable ammonium and mobile sulfur.

[5] GOST R 54650-2011. Soils. Determination of mobile compounds of phosphorus and potassium by the Kirsanov method.

[6] GOST 26489-85. Soils. Determination of exchangeable ammonium.

[7] GOST 26951-86Soils. Determination of nitrates by the ionometric method.

Fig. 1. Soil profiles and locations of moose chyme at experimental sites.

soil layers, the ammonium concentration in the experimental samples was higher than in the control by 185.6–267.3% in the forest, by 16.8–18.0% in the field, and by 27.1–29.7% in the deforestation site. The concentration of NH_4^+-N in the control plots is similar in different biotopes, but the maximum values are noted in the overgrown field, where herbaceous vegetation grows more abundantly (Fig. 3).

A higher concentration of N-NO_3^- was recorded in all biotopes and in both soil layers where the liquid fractions of chyme had penetrated (Fig. 4). The maximum concentration of nitrate nitrogen in the upper soil layer was 14.8 mg/kg in the forest, 18.6 mg/kg in the field, and 16.6 mg/kg in the deforestation area. In the control, the maximum value of this compound in the upper layer was 7.9 mg/kg (forest), 4.0 mg/kg (field), 8.9 mg/kg (deforestation area). The concentration of N-NO_3^- in the soil under the chyme piles exceeded the control 1.5–2.5 times (on average), and only in the upper layer in the field – 4.5 times. The concentration of nitrate nitrogen in the upper soil layer in the experiment exceeded that in the control in the forest by 133.7%, in the field – by 345.8%, in the deforestation site – by 117.8%, and in the lower soil layer – by 121.3%, 95.1%, 58.3%, respectively.

The concentration of ammonium in the soil is higher than the quantity of nitrates, with the exception of two samples in the experiment at the deforestation site. The comparison of the NH_4^+-N / N-NO_3^- ratio demonstrates differences between biotopes with the dominance of woody vegetation (forest and deforestation site) and herbaceous vegetation (field). In the control samples, the upper soil layer in the forest and the deforestation site contained more ammonium nitrogen (NH_4^+-N / N-NO_3^- = 4.17 ± 0.96 and 3.93 ± 1.39, respectively) than in the lower layer (2.03 ± 0.18 and 2.15 ± 0.08). In the field site, the predominance of ammonium over nitrates was several times greater, but the differences between the soil layers were almost imperceptible (19.83 ± 2.46 and 19.37 ± 2.19). This is due to the fact that low-growing grass vegetation with a poorly developed root system does not have time to utilize the ammonium nitrogen available in the overgrown field, unlike woody and shrubby vegetation in the forest and in the deforestation site.

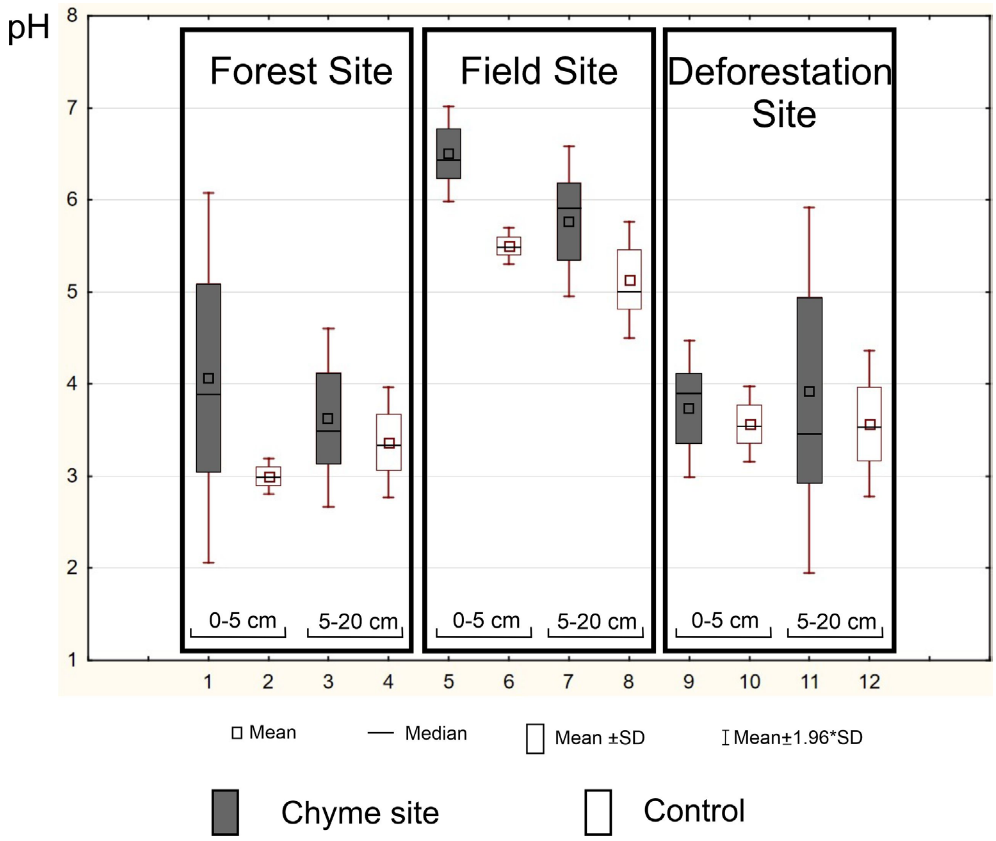

Fig. 2. Soil acidity in experimental and control sites.

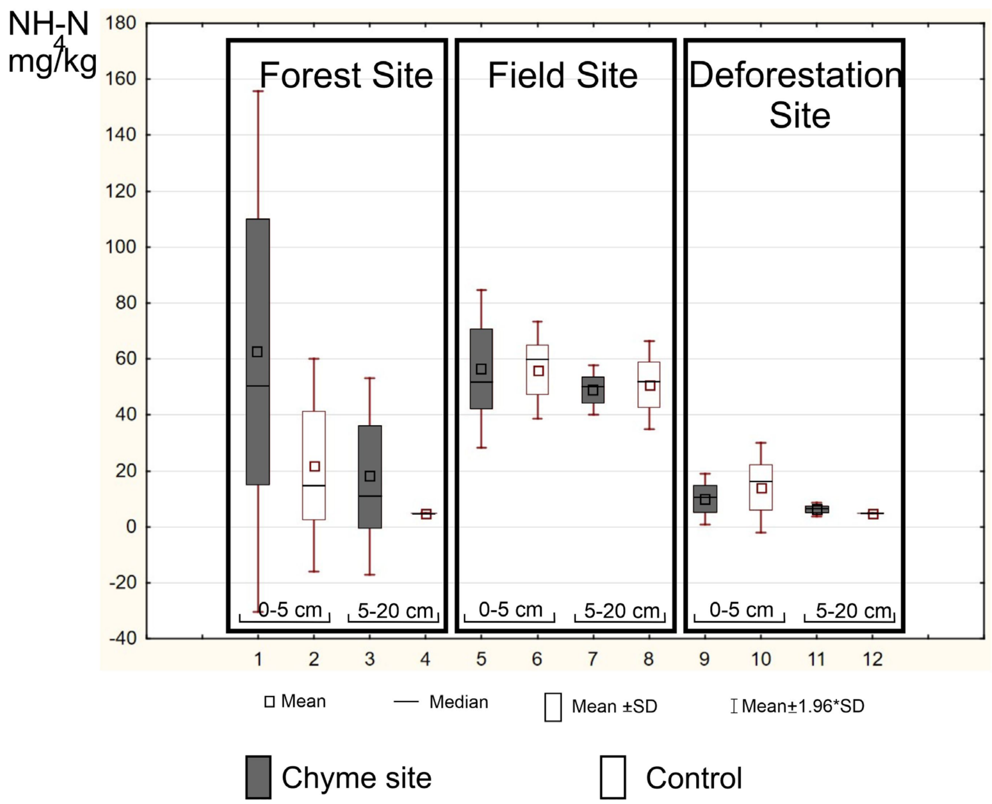

Fig. 3. Ammonium nitrogen in experimental and control sites.

The situation changes after the chyme fractions infiltrate the soil. Due to the excessive nitrogen, the ammonium concentration in the upper and lower soil layers in the forest slightly increases (the ratio NH_4^+-N / N-NO_3^- = 5.27 ± 1.22 and 2.90 ± 0.78, respectively), in the deforestation site it slightly decreases (2.43 ± 1.59 and 1.90 ± 0.70), and in the field it drops sharply (4.40 ± 0.29 and 11.17 ± 3.47). Thus, the penetration of large volumes of nitrogen into the soil leads to stimulation and acceleration of the nutrient cycle and, probably, to intensification of the activity of microorganisms in soil. In an overmature forest with a low projective cover of grass and shrub vegetation, ammonium nitrogen accumulates in the upper soil horizons since the main biomass of the root systems is concentrated in deeper layers, and the activity of microorganisms is suppressed by toxic components from the coniferous litter. On the contrary, in the deforestation site, the surface layers of the soil are densely covered with the root systems of immature plants of the undergrowth and grasses, actively absorbing the incoming nitrogen. In the field site, under aerobic conditions of the near-surface soil layer, ammonium is rapidly transformed into nitrates due to the high activity of the soil microbiome.

In terms of the content of mobile phosphates, the soil under the chyme piles and in the control differ most significantly because P_2O_5 is not actively transformed, unlike nitrogen-containing compounds. In the upper soil layer under the chyme piles, there are 6.0–25.0 times more phosphates than in the control plots (Fig. 5). In the field site, there were 899.3 ± 19.4 mg/kg (by 639%) more phosphates in the upper soil layer and 341.3 ± 41.1 mg/kg (by 219%) in the lower layer in the experiment than in the control. The maximum concentration of mobile phosphates at the points with chyme in the field site was 1.1 g/kg in the 0–5 cm layer. In the forest site, in a pairwise comparison of the upper layers, P_2O_5 was 1451% higher in the soil under the influence of chyme than in the control, and in the deforestation area this difference was even higher – by 2208%. The differences in concentration of phosphates between the upper and lower soil layers in different biotopes, both in the experiment and in the control, did not exceed 3.5 times. There were more phosphates in the upper layer in the forest. A higher concentration of phosphates was found in the lower layer in certain samples in the field site and in the deforestation site due to high soil porosity.

The quantity of K_2O exceeded the share of mobile phosphates (Fig. 6). The highest concentrations of mobile potassium were recorded under chyme piles in the forest and in the field sites. The highest concentration of potassium was noted in the upper soil layer in the forest – 2.5 g/kg. Here, K_2O concentration in the experimental samples was 1164.7 ± 505.6 mg/kg (554% higher than in the control). The quantity of potassium in points under the chyme was 1085.7 ± 107.5 mg/kg (637% higher than in the control) in the upper soil layer in the field site. In general, the difference of potassium concentration in the upper layer between the experimental and control samples was very significant: in the forest site it was 6.5–8.0 times higher, in the field site – 5.2–7.4 times, in the deforestation site – 2.1–7.5 times. Both in the experiment and control plots, the K_2O content in the 0–5 cm layer was higher than in the 5–20 cm one: in the forest, it was 3.0–14.5 times higher, in the field –1.2–3.5 times, in the deforestation –1.4–7.2 times.

The ratio of nitrogen and phosphorus compounds in soils differs significantly between the experimental and control sites (Table 1). The amount of nitrogen compounds overcomes over phosphorus compounds (N : P ratio = 1.0 : 0.6) in the moose chyme. However, in soils of the experimental sites, a remarkable prevalence of mobile phosphates over nitrogen compounds was observed (Table 1) that indicates active utilization, transformation and migration of nitrogen-containing compounds from liquid fractions of the chyme. At the same time, the chemical composition of the soil profile differed noticeably in different biotopes.

The significant enrichment of the surface soil layers with nutrients occurs with the initial entry of chyme components into the soil. However, by the end of the growing season, nitrogen compounds are utilized by soil microbes and plants to a greater extent than phosphorus-containing compounds that dramatically changes the N : P ratio. Redistribution of incoming organic waste in the soil profile depends on its structure. In a forest with a textured thick litter, chyme fractions are retained longer in the upper soil layer and are actively immobilized by microorganisms. On the contrary, in a deforestation area with completely transformed soil horizons and their high porosity, chyme fractions pass more quickly into the deepest soil layers since they are more easily washed out by precipitation. In an overgrown field, a more active utilization of nitrogen compounds occurs in the upper soil layer, but owing to the sandy structure, nitrogen compounds gradually move down the soil profile. Here, they are retained due to the underlying layer of clay deposits that is reflected in a higher concentration of nitrogen in the 5–20 cm layer (Table 1). The nitrogen and phosphorus ratio is quite stable in soils of the control plots (Table 1). There is a slight tendency to decrease nitrogen concentrations in the lower soil horizons in the control.

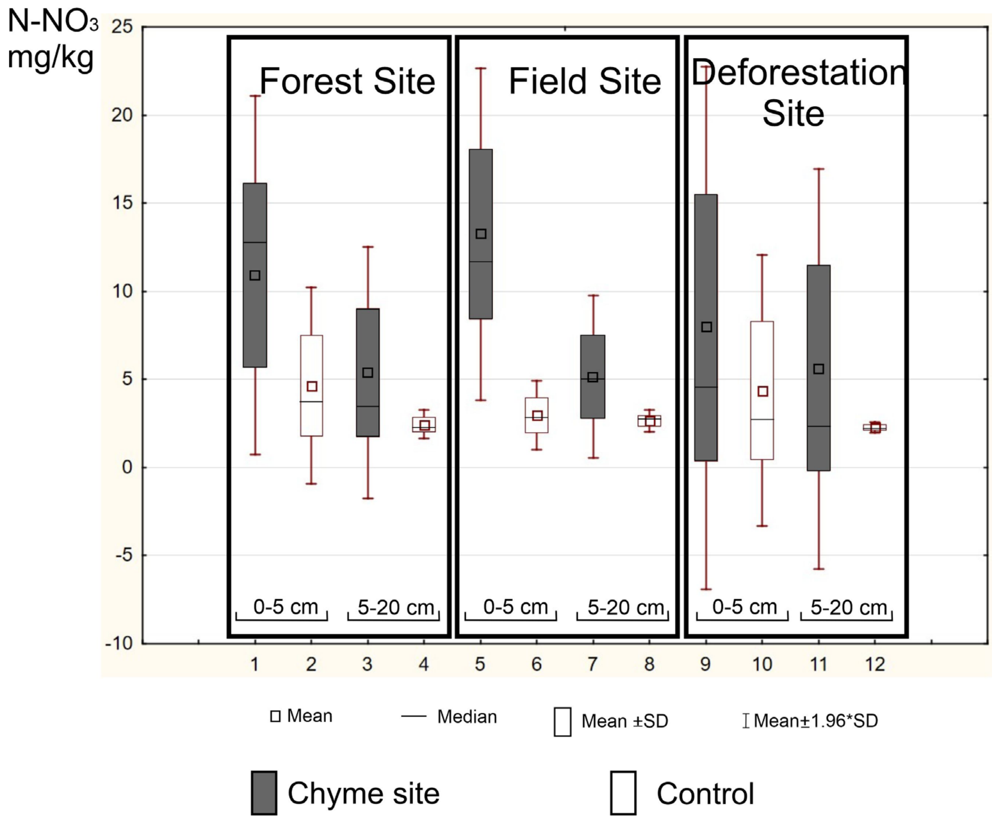

Fig. 4. Nitrate nitrogen in experimental and control sites.

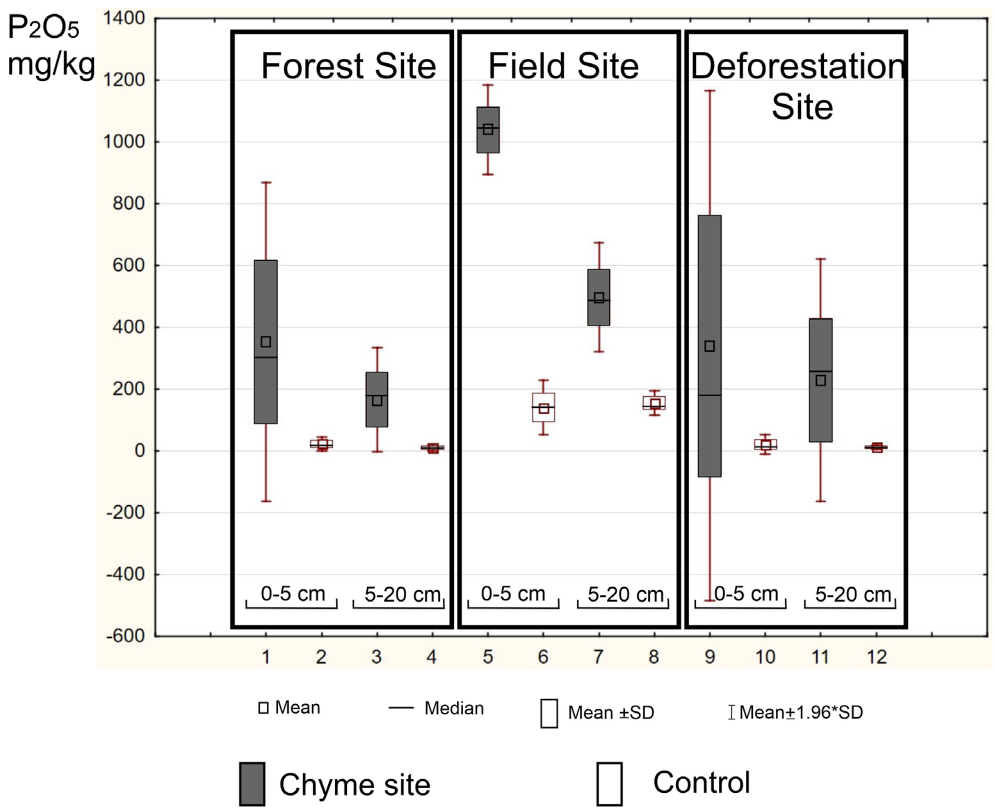

Fig. 5. Mobile phosphates in experimental and control sites.

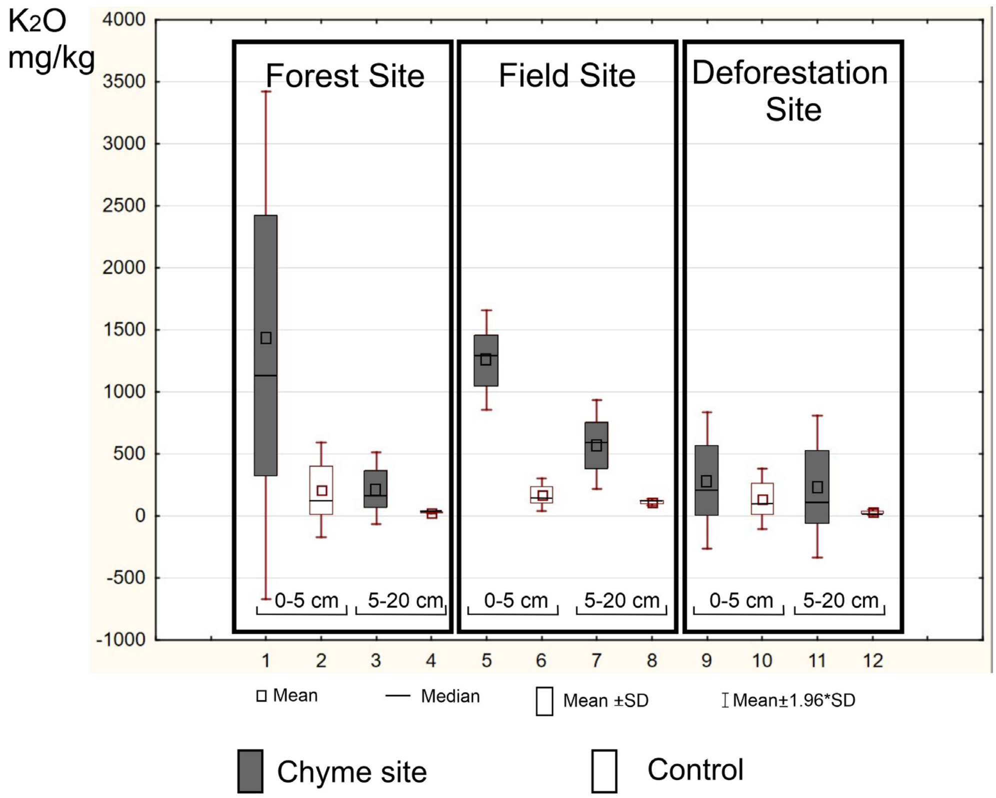

Fig. 6. Mobile potassium in experimental and control sites.

The ratio of mineral nitrogen to available potassium has a similar trend. The concentration of potassium in soils is higher than phosphorus both in the control and in the experiment (Table 1, Fig. 6). In the control, the highest potassium to nitrogen ratio is in the areas with woody and shrubby vegetation (forest and deforestation) and less in the overgrown field (Table 1). The highest potassium to nitrogen ratio is in the uppermost soil layer. This confirms the known facts that the quantity of potassium in soil is higher in the upper horizons and their pool is especially large under the canopies and roots of plants (Schlesinger, 2021). After laying out of chyme, there is a sharp prevalence of potassium over nitrogen (Table 1) since the utilization of chyme nitrogen in the soil occurs faster than potassium. Due to the high concentration of potassium in the chyme and soil, the differences for this compound between various biotopes are smoothed out. However, in the upper layer, more mobile potassium is retained in biotopes with distinct horizons (forest and field sites). No differences in the ratio of nitrogen to potassium are found between the analyzed soil layers in the transformed (homogeneous in structure) soil of the deforestation area.

Discussion

The entry of various forms of fertilizers into soil in large volumes stimulates the activation of eutrophication, and especially widespread nutrient enrichment of soil is noted when using organic fertilizers of animal origin (Semenov et al., 2023). Soil is enriched by any biological components of a vertebrate animal: droppings, manure, carcass remains, gastrointestinal tract contents, and even natal fluids and tissues (Ferraro et al., 2023; Hobbs, 1996), creating special zoochemical hotspots of nutrients in the ecosystem.

Microbes and invertebrates actively and quickly utilize substances from these biological excretions and wastes providing faster decomposition of the litter and intensification of nutrient cycling (Ritzenthaler et al., 2018). Meteorological conditions (especially droughts and precipitation) can adjust the speed of this cycle. For example, heavy rains can contribute to leaching of many elements from soil before they are processed by microorganisms and incorporated into organic matter (Ritzenthaler et al., 2018).

In boreal forests, the application of various fertilizers increases the concentration of nutrients in forage plants that contributes to the growth of productivity of the hunting lands for wild ungulates

Table 1. Ratio of mineral nitrogen and mobile phosphorus and potassium in soils in four months after laying out of moose chyme.

Biotope	Soil layer	Experimental plots	Control	Experimental plots	Control
		NH_4^+-N+N-NO_3^- : P_2O_5	NH_4^+-N+N-NO_3^- : P_2O_5	NH_4^+-N+N-NO_3^- : K_2O	NH_4^+-N+N-NO_3^- : K_2O
Forest site	0–5 cm	1 : 4.8	1 : 0.8	1 : 21.5	1 : 7.8
	5–20 cm	1 : 7.1	1 : 1.5	1 : 11.7	1 : 3.8
Field site	0–5 cm	1 : 14.9	1 : 2.4	1 : 19.3	1 : 2.9
	5–20 cm	1 : 9.2	1 : 2.9	1 : 10.7	1 : 2.1
Deforestation site	0–5 cm	1 : 19.0	1 : 1.2	1 : 15.3	1 : 7.0
	5–20 cm	1 : 19.4	1 : 1.7	1 : 15.5	1 : 4.4

(Manush, 1971). This ultimately determines more frequent and willing visits of these herbivores to such forage areas (Ball et al., 2000; Budnichenko and Stelmakh, 1986; Edenius, 1993).

The experience with using the rumen contents of wild ungulates as a source of fertilizers has not been described, although there is some information on the use of chyme from livestock as a fertilizer on nutrient-poor tropic soils (Edeh et al., 2015). These and other new types of organic fertilizers have not been studied at all in terms of their impact on the environment (Kulek, 2015). However, in general, it has been noted that the maximum increase in plant productivity is observed when providing the soil with one-time applications of organic fertilizers (Goulding et al., 2013).

An active enzymatic and microbial breakdown of easily digestible carbohydrates, fiber and proteins occurs in the gastrointestinal tract of ungulates (Kochanov et al., 1981; Veber et al., 1992). The stomach of ruminants is the main organ of fermentation and digestion of food; therefore, its contents (chyme) are a matter enriched with biologically active substances. However, the chemical composition of chyme can be highly variable due to the heterogeneity of the qualitative composition of the consumed feed, the diversity and concentration of symbiotic microorganisms.

Nitrogen metabolism in the rumen of ungulates is based on the circulation of ammonia, urea, protein and non-protein nitrogen, and amino acids (Kharitonov, 2019; Van Soest, 1994; Veber et al., 1992). In the autumn-winter, more than half of the total nitrogen in the moose rumen chyme is represented by amino nitrogen, i.e. free amino acids – the main components of the symbiont rumen microflora (Veber et al., 1992). Phosphorus in the winter chyme is only in the composition of the consumed feed. This element is practically not absorbed and is quickly removed with feces (Kochanov et al., 1981).

The moose stomach accounts for 10–12% of the animal's body weight, but it is usually only half full (Sablina, 1970; Veber et al., 1992). The maximum mass of chyme in the rumen of moose in autumn reaches 40 kg, and in winter it does not exceed 30 kg (Filonov, 1983). In our experiment, we used a sample of the chyme weighing 5 kg. This corresponds to an organic matter application rate of 100 t/ha. Placing the chyme on the soil surface in large volumes can have an eutrophication effect not only on the surrounding vegetation, but on the entire soil profile, inhibiting its self-restoration processes (Kudeyarov and Semenov, 1991; Nikitishen, 1984). Moreover, such an effect can persist for several growing seasons. This is similar to the application of manure from domestic ungulates. Feces also contain easily mineralized nitrogen, and the application of such fertilizers improves nitrogen nutrition of plants. However, nitrogen utilization by plants is not observed to the fullest extent in the year of manure application (Sychev, 2019).

The concentration of macronutrients is significantly lower in the autumn-winter moose chyme than in the cattle rumen contents (Kharitonov, 2019); in terms of nutrient concentrations it is more similar to the droppings of goats, cattle and partially horses, although these fecal indicators vary greatly (Pagliari and Laboski, 2012). The concentration of macroelements in the moose rumen contents is approximately equivalent to their amount in the leaves of broad-leaved trees, shrubs and herbs and is noticeably higher than in the plant litter of pine forests, both in nitrogen and phosphorus (Remezov et al., 1959). Therefore, moose chyme can be considered as a concentrated complex of nutrients that can enrich the soils of taiga ecosystems.

In all analyzed control plots, the high organic upper soil layer had, on average, a higher acidity than the lower layer (Fig. 2). This is a known pattern (Lukina et al., 2008). After the entry of the moose chyme, a sharp shift in the soil acidity towards neutrality occurred in all biotopes, being especially noticeable in the upper soil layer (Fig. 2). This occurred because of the penetration of liquid substances of the chyme, which have a neutral acidity. In the upper soil layer in the forest, the pH level was 35% higher compared to this indicator from the soil samples in the control. In the field, this difference was 18.2%, in the deforestation site – 6.2%.

The incoming fractions of the chyme change the established system of interaction between organic and mineral components of soil (stabilization-destabilization), and most likely suppress the development of microscopic fungi, bacteria and some plants responsible for the production of organic acids and, accordingly, for soil acidification (Shamrikova, 2013). The effect from the chyme is similar to the application of manure, which reduces soil acidity (Ferreira et al., 2021; Semenov et al., 2023). Therefore, it is often recommended to use fertilizers that increase soil pH levels to stimulate plant growth and development (Smith et al., 2020). The decrease in soil acidity, in turn, leads to the high activity of soil invertebrates involved in the decomposition of organic matter (Shamrikova, 2013). Additionally, by incorporating manure into soil and subsequently increasing pH, soil aggregates are stabilized, their resistance to water increases, and a long-term pool of high nutrient concentrations is created (Zain et al., 2023).

In general, in the taiga zone of the European North-East of Russia, the distribution of nitrogen in soil after the application of nitrogen-containing fertilizers is approximately balanced in the following ratio: about 50% of nitrogen is concentrated and adsorbed in soil and underground vegetation, 30% is absorbed by plants, 15% is washed off by runoff and 5% migrates to deeper soil layers (Beznosikov, 2001).

Nitrogen is a key biogenic element of the taiga ecosystem, the deficiency of which affects the productivity of vegetation directly (Bazilevich and Titlyanova, 2008). The concentration of mobile forms of nitrogen in soils primarily depends on its total reserves and mineralization-immobilization interactions (Semenov, 2020). The intensity of the nitrogen cycle in soil strongly determines the characteristics of the biotope and weather conditions. For example, the biological cycle of nitrogen is more intensive in spruce forests compared to pine forests, but its reserves there are lower since nitrogen is actively processed by soil microorganisms (Fedorets and Bakhmet, 2003).

The concentration of nitrogen in the moose chyme is primarily determined by the chemical composition of the food consumed. The level of nitrogen concentration in shoots of woody and shrubby food plants in winter varies from 0.6 to 2.1% of absolute dry matter (Dunin and Kozlo, 1992) that is within the range of detectable nitrogen concentrations in the rumen contents of moose. However, the level of nitrogen in the chyme of individual ungulates can vary greatly even when using a uniform diet. It is known that the concentration of nutrients in winter food plants of a certain species can vary 1.5–2.0 times (Ahlen, 1975). For example, in new deforestation areas, birch shoots consumed by moose contain more crude protein than in overgrown logging territories (Wam et al., 2016).

As crude protein intake in ruminants increases, nitrogen concentrations in gastrointestinal contents, feces, and urine also rise (Cole et al., 2006). Nitrogen concentrations tend to be higher in high-energy, easily fermentable forages and they are lower in low-energy, high-fiber ones because nitrogen readily binds with cellulose. Condensed tannins from woody forages can attach nitrogen-containing compounds within the chime thereby reducing the rate of ammonium synthesis in the rumen. As a result, the presence of condensed tannins in the rumen can lead to increased fiber concentrations in the intestinal contents, including feces (Norris and Smith, 2020). Moose typically consume a diet rich in tannin-containing plants, which promotes nitrogen binding in the stomach. However, this nitrogen from plant residues in the rumen contents can be used as a potential fertilizer.

The NH_4^+-N concentrations between experiment and control in all biotopes differ slightly (Fig. 3). With chyme introduction to soil, there is the transformation of the incoming forms of organic nitrogen from rumen digesta residues in the process of ammonification during the growing season. The newly formed ammonium is actively absorbed by plant roots. The same part of ammonium that has not had time to be absorbed under aerobic conditions by microorganisms is quickly transformed to N-NO_3^- (Barber, 1988; Keeney and Hatfield, 2008). This is especially typical for the upper soil horizons. Since moose chyme contains a lot of nitrogen in the form of amino acids, it can be assumed that this nitrogen will be largely immobilized in soil (Nikitishen, 1984; Semenov, 2020). Thus, after NH_4^+-N and N-NO_3^- enter the soil profile from the surface, this organic nitrogen is gradually mineralized by microorganisms and eventually becomes available to plants (Follett, 2008; Katz, 2020).

In our experiment, liquid fractions of the chyme penetrating from the surface lead to an increased concentration of nitrogen compounds in the upper soil layers. The maximum ammonium concentrations are observed in the forest with dense litter. The retention of nitrogen in coniferous forests is facilitated by the high content of polyphenols in organic-rich horizons (Lukina et al., 2008). In contrast, the lowest amount of ammonium is recorded in the deforestation area with completely transformed soil cover, easing the accelerated leaching of this compound from soil (Fig. 3).

Losses of nitrogen added into the soil occur due to the formation of ammonia, as well as during denitrification (Hiis et al., 2024; Semenov, 2020). Ammonia is one of the main components of the chyme of ungulates, which easily dissolves in rumen fluids; it is absorbed into blood and converted into urea in the liver (Membrive, 2016; Van Soest, 1994). The maximum concentration of ammonia in the moose rumen is observed in the autumn-winter, when the general decrease in the quality and quantity of food leads to fall in the diversity and concentration of bacteria producing and consuming ammonia (Veber et al., 1992).

Microbial, ammonium and non-ammonium nitrogen from the chyme is transformed under the action of soil organisms into ammonium compounds with the release of ammonia. The deposition of chyme on the soil surface accelerates the process of ammonia volatilization (Katz, 2020). Therefore, ammonia volatilization into the environment should be more significant than its losses due to leaching, for example, from ungulate droppings. For example, nitrogen volatilization from cattle feces is quite low (from 1 to 13%) due to slow mineralization of organic matter (Pagliari et al., 2020).

The analysis of soils in experimental biotopes shows a significant level of nitrate ion at the site with the chyme that exceeds the control indicators (Fig. 4). In accordance with the known categories of provision of agricultural crops with nitrogen compounds (Nikitishen, 2003), most of our samples in the forest and in the field under the influence of chyme can be classified as high and in the deforestation area as medium values of soil nitrogen richness.

NH_4^+-N and N-NO_3^- are highly soluble in water and can migrate through the soil profile and even enter groundwater due to precipitation (West and Nelson, 2018). When the optimal nitrogen level exceeds, it migrates through the soil beyond the plant root zone.

The distribution of nitrogen-containing compounds along the profile is determined by the properties and structure of soil. NO_3^- leaching is enhanced on light sandy soils, and a significant amount of NH_4^+-N can be fixed in loams (Barber, 1988; Follett, 2008; McNeill and Unkovich, 2007; Nikitishen, 1984).

In general, up to 30% of nitrogen can be lost in nitrification and denitrification (Barker and Collins, 2018). As the result of these processes, after entering the chyme, the ammonium concentration in soil begins to approach background (control) values by the end of the growing season.

Phosphorus and potassium have a clearly expressed eluvial-illuvial distribution and the variability of their content decreases with soil depth (Fedorets et al., 2006). Potassium is a highly mobile element and is easily washed out from plants, litter and soil; hence, its concentration is highly fluctuating in mineral horizons (Fedorets et al., 2006). In hunting grounds, a lot of potassium appear in soil with the urine of wild ungulates (Kochanov et al., 1981; Veber et al., 1992).

Potassium is actively absorbed by trees and shrubs; that is why its concentration is usually lower in habitats dominated by these plants (Lukina et al., 2008). Our data confirm this statement. A higher concentration of mobile potassium in the experiment is noted in the overgrown field, and much less in the deforestation area and in the lower soil layer in the forest. However, an extremely high concentration of K_2O is observed in all plots with chyme. Lots of it is accumulated in the upper layer of the forest soil (Fig. 6). This concentration is several times higher than necessary for plant growth (Barber, 1988; Nikitishen, 2003). Potassium from organic fertilizers usually does not penetrate into the deep soil horizons (Nikitishen, 1984). Plants always maintain a potassium reserve in soils above their potential consumption (Schlesinger, 2021). Therefore, the predominance of potassium over mineral nitrogen is more noticeable against the background of intensive utilization of mineral nitrogen from chyme in soils from biotopes with higher plant biomass (forest, deforestation area), unlike the grass community (field).

Phosphorus in the rumen contents is represented by compounds from forage plants and mainly from animal saliva (Cohen, 1980). Most of the manure phosphorus is difficult to leach from soil, since it is a low-mobility element (Barker and Collins, 2018), so the application of manure always replenishes the phosphorus deficiency in the terrestrial ecosystem (Sychev, 2019).

The pollution of habitats is observed at the constant application of large one-time concentrations of phosphorus, exceeding the needs of plants (Weddin and Russelle, 2020; West and Nelson, 2018). Many phosphorus compounds are adsorbed by clay particles in soil (Pagliari et al., 2020; Sharma, 2020).

Most phosphorus in manure is present in various soluble and insoluble forms of inorganic phosphate. The existence of specific phosphorus compounds depends on pH of the manure and the specific types of metals in its composition (Pagliari et al., 2020). High pH due to adding chyme and other organic matter leads to a decrease in phosphorus solubility in a soil solution (Nikitishen, 1984).

We have established that the concentration of mobile phosphates at the end of the growing season remains at a very high level (Fig. 5, Table 1) and, unlike nitrogen-containing compounds, is poorly used by plants and microorganisms. The concentration of mobile phosphates noted in our experiments is several times higher than the phosphorus nutrition standards for plants, and such a high level of phosphates can persist in the soil for several years (Nikitishen, 2003).

Feces and urine waste, containing high concentrations of nitrogen and phosphorus, can negatively affect the livestock environment by polluting soils and waters (West and Nelson, 2018). This is a common drawback of all pasture ecosystems, which are characterized by uneven fertilization with manure (Follett, 2008). The application of large volumes of fertilizers with the N : P ratio close to 1 : 1 can lead to negative consequences - the accumulation of excess phosphorus (Smith et al., 2020). For moose chyme, this ratio is 1 : 0.6, but it is far from optimal – 4 : 1 (Smith et al., 2020). Therefore, in habitats where chyme has been laid out, we observe the increased phosphorus concentration. It is necessary to redistribute the remains of the moose chyme left after hunting over a larger area, or better yet, bury them, in order to reduce both the loss of nitrogen compounds (through volatilization) and phosphate concentrations. This will preserve the chyme nutrients in the soil for plants. In particular, it has previously been established that numerous small piles of dung excreted by wild ungulates make their nutrients more accessible to plants than large piles (Bakker et al., 2004; Pastor et al., 1993). Uneven distribution of hunting biological waste over the grounds is similar to a one-time application of organic fertilizers, and in the long term, this will not have a negative impact on the environment. Another technology is composting the moose rumen contents. As is known, the forms of nitrogen in the composted manure are much more stable and act as a source of nutrients for plants for a longer period (Eghball, 2004; Sharma, 2020).

Conclusion

Laying out of moose rumen contents onto the soil surface becomes the cause of eutrophication in all experimental biotopes. The noticeable enrichment with macroelements in the uppermost soil layer is observed due to the chyme. As the result, a sharp increase in soil pH occurs. In a forest with a thicker litter and a structured soil, the chyme infiltrates are preserved and function longer in the upper soil layer and diffuse more slowly down the profile. Therefore, the chyme components will act as a source of nutrients longer in forest habitats than in overgrown fields and deforestation area.

The high concentration of nitrogen, phosphorus and potassium in the soil under chyme piles even at the end of the growing season allows us to consider this type of hunting biological waste as a point source of eutrophication in ecosystems in the short term. However, the chyme can act as a pool of nutrients in soils for several growing seasons. Rational use of biological waste will contribute to enrichment of the soil profile with nutrients and stimulate their circulation in taiga ecosystems.

In northern territories, where the people do not use livestock manure and composts as a source of nitrogen, the contents of the moose gastrointestinal tract can be considered as its analogue, i.e. as a potential source of organic fertilizers in agriculture.

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