



RESEARCH ARTICLE

Ecological Functions and Biogeochemical Role of Drained Pond Soils in Agroecosystems

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The main conclusions of the article are based on data from experiments conducted at the experimental-production site "Sharkovshchinsky" in the Sharkovshchinsky district of Vitebsk Oblast (drained in 1968), Lake Opytnoye in the European Northeast of Russia, drained lakes of the tundra, steppe lakeside landscapes of northern Kulunda, and analysis of maps from the National Soil Atlas of the Russian Federation. Drainage of lakes results in soils that, with a systematic approach, can be effectively used in agriculture. The study demonstrates the feasibility of applying experience from research on drained pond soils to analyze high-risk soils, plan crop rotations, develop land-use strategies, and support their practical application in agriculture.

INTRODUCTION

According to various sources, approximately 700 lakes, wetlands, and ponds have disappeared in Moscow alone as a result of anthropogenic impact, with their territories subsequently allocated for urban development [15]. According to the Space Research Institute of the Russian Academy of Sciences (IKI RAS), the rate of natural transformation of waterlogged peatland areas reaches 430 thousand ha year⁻¹ [16]. These processes indicate the emergence of vacant territories potentially suitable for use in the agro-industrial sector. In this regard, the study of drained pond soils is becoming increasingly relevant within the framework of future agronomic development. Currently, there are approximately 2,200 artificial reservoirs within the territory of Russia, which may also be reclaimed in the future for subsequent agricultural use. The highest pond density is characteristic of the southern regions of the European part of the country, located within the forest-steppe and steppe zones, where they were originally created for agricultural purposes [17]. The area of commercial fish-farming ponds currently amounts to approximately 1,500 km² [18].

Similar soils developed on glaciolacustrine clays and studied in different regions of Russia and Belarus may serve as a source of information for comparative analysis. They exhibit a well-defined two-membered profile structure that is not geological in origin but associated with pedogenic processes. At depths ranging from 1.0 to 1.5 m, varved clays are well preserved and contain silty material between the layers and, in some cases, within them. In the most waterlogged (gleyic) soils, horizontal sections of the layers display displacements, heterogeneities, and iron hydroxide mottles. Upward along the profile, turbation features become apparent, as reflected in Tables 1 and 2 [14].

Table 1: Duration of Excessive and Insufficient Soil Moisture in Weeks for Soils Developed on Glaciolacustrine Clays, 0–20 cm Layer

Degree of Soil Waterlogging	Excessive Moisture (Full water capacity–field capacity)		Insufficient Moisture (Moisture content below the capillary rupture point–wilting point)	
	Undrained	Drained	Undrained	Drained
Temporarily overmoistened	2.5–6 weeks	Up to 2.5 weeks	4–13 weeks	5.5–21.5 weeks
Gleyic	7–17 weeks	3–7 weeks	Up to 8.5 weeks	5.5–18.5 weeks
Gleyed	11–25 weeks	4–11.5 weeks	Up to 3 weeks	3–10 weeks

The establishment of a periodically leaching water regime following drainage contributes to changes in the morphological structure of the soil profile, visually manifested by improved structural condition, increased cracking, changes in the coloration of soil horizons, as well as indications of downward migration of organic matter and fine fractions within the soil mass. In addition, physiologically important elements are removed from the upper horizons together with the clay fraction [3, 4].

Table 2: Duration of Perched Water Persistence within the 0–50 cm Layer, Weeks

Years Classified by Precipitation Supply	Degree of Soil Waterlogging					
	Temporarily excessively moist		Gleyic		Gleyed	
	Undrained	Drained	Undrained	Drained	Undrained	Drained
Humid	2–3 weeks	Less than 1 week	10–11 weeks	3.5–7 weeks	14–20 weeks	5.5–6.5 weeks
Normal	1–2 weeks	0	6–9 weeks	2–3 weeks	9–12 weeks	4–6 weeks
Dry	0.5–2 weeks	0	3–4 weeks	1–1.5 weeks	7–8.5 weeks	3.5–4 weeks

Drainage reclamation has altered the soil water regime and enabled the use of previously uncultivated territories in agriculture. The reduction in the degree of waterlogging was reflected in the morphological structure of the soil profile. As a result of the establishment of a periodically leaching water regime and intensified nutrient leaching through surface and drainage runoff, high efficiency in the use of drained soils can only be achieved through the application of adaptive farming systems, agrotechnical and agricultural and land-reclamation measures, combined with increased fertilizer application rates.



Figure 1: Photographs of landscapes of the studied drained lake basins [7].

Climate substantially affects the hydrological regime of soils by determining the water and heat balance through the ratio between precipitation and evaporation, thereby intensifying or weakening the processes of leaching and eluvial–illuvial translocation of substances. Under the influence of climatic factors, including radiation balance and sums of active air temperatures, a temperature gradient forms within the soil, regulating heat exchange, condensation, and moisture

evaporation. In drained soils developed on glaciolacustrine deposits, this contributes to the improvement of subsurface horizon structure through the formation of pores and cracks [1, 2].

Soil freezing begins from the surface at a temperature of $-1\text{ }^{\circ}\text{C}$, causing the phase transition of water into ice, migration of moisture toward the freezing zone, and a decrease in hydraulic conductivity by one to five orders of magnitude. This alters the water potential and leads to groundwater redistribution; up to 20% of the ice forms due to upward capillary water movement. Thawing enhances filtration and improves structural organization, particularly in drained systems, increasing the mobility of humus and nutrient elements.

Comparison with undrained analogues developed on glaciolacustrine deposits (prior to reclamation carried out in the 1960s–1980s) demonstrated that filtration rates in drained soils increased by 5–10 times relative to undisturbed soils. Soil structure improved, exhibiting greater porosity and cracking; particle-size distribution shifted toward coarser fractions compared with the more clayey and silty waterlogged analogues. The removal of excess moisture alters the hydrological regime, resulting in the eluviation of humus and Fe–Mn compounds. In samples of undrained soils, by contrast, low water permeability and stagnation of excess moisture are observed.

All these processes lead to the formation of new diagnostic horizons with improved structure — genetic soil layers possessing a complex of morphological, physical, and chemical properties that clearly reflect genesis, evolution, and modern processes and are used for soil classification [6]. Within these horizons, changes in the water balance accelerate and pedogenesis intensifies, analogous to the effects of freeze–thaw cycles, where changes reached up to 50% over 10 days, with a pronounced emphasis on filtration and mobility of substances [1, 2].

A comparative analysis of several studies was conducted. Climate constitutes an integral component of hydrological conditions. Table 3 examines several different natural zones. Lake Opytnoye, whose location is shown in Figure 2, is situated at $68^{\circ}30'$ N latitude and $64^{\circ}30'$ E longitude, on a hilly moraine plain at an elevation of 100–250 m above sea level, between the Pechora River and the Pai-Khoi Ridge.



Figure 2: Location of Lake Opytnoye [7].

During the 1960s–1970s, within the framework of the Soviet program aimed at creating a forage base for cattle breeding in the Far North, artificial drainage of thermokarst lake basins was carried out. Sown and fertilized plots produced high hay yields for 5–6 years; however, tundra moss-lichen and shrub communities subsequently displaced agricultural crops, leading to the cessation of production.

In the 1970s–1980s, approximately 40 lakes with a total area of about 1000 ha were drained in the European North. The largest site was Lake Opytnoye, which became a key research object [6, 7]. Table 3 also presents data on soils near Lake Bagan, located in the southern part of Novosibirsk

Oblast within the Baraba Lowland at an elevation of 100–110 m above sea level [8].

Table 3: Comparative Analysis of Main Climatic Parameters

Soil Type	Location	Climate	Mean Annual Temperature	Precipitation
Peat-permafrost soils	Lake Opytnoye basin, Bolshezemelskaya Tundra	Arctic	-12 °C	200–300 mm
Drained gleyed soils	Glaciolacustrine deposits	Moderately cold	-9 °C	300–400 mm
Light-humus stratozems	Northern Kulunda, Lake Bagan	Continental steppe	+3 °C	250–350 mm

Considering soil hydrology, it becomes evident that the Arctic climate determines the formation of peat-permafrost soils. Cold climatic conditions lead to the natural drainage of lakes as a result of erosion of ice-rich deposits; surface runoff occurs along the active layer, initiating the process of soil genesis. The result is meadow paludification. In drained gleyed soils, reclamation has led to a reduction in moisture content and the re-oxidation of iron and manganese compounds. Eluvial-illuvial processes are initiated: humus migrates from the upper horizons, the clay content decreases by 5–10%, while calcium, potassium, and magnesium accumulate in the lower horizons; iron and aluminum precipitate within the illuvial horizon.

Light-humus stratozems formed as a result of sharp fluctuations in lake water level, during which groundwater levels decrease to 45 cm in humid years. The lowering of groundwater levels stimulates vegetation emergence, as well as seed growth and development.

Based on the data presented in Table 4, the processes occurring within the soils can be clearly identified. In peat-permafrost soils of the Bolshezemelskaya Tundra, artificial drainage leads to accelerated soil genesis and paludification of territories. Hydraulic isolation by the frozen layer and surface runoff cause a decrease in water level, accelerating pedogenesis. Drainage resulted in horizon transformation: humus-gley horizons became eluviated bleached horizons, illuvial-gley horizons transformed into illuvial horizons, and gleyed horizons changed into transitional BCg horizons characteristic of podzolic soils.

Drained gleyed soils differ only in the lower layer, where transitional-type soils are secondarily oxidized. However, pronounced biogenic accumulation should be noted.

Table 4: Comparative Analysis of Main Hydrological Parameters

Soil Type	Groundwater Level	Particle-Size Composition	Filtration Coefficient (water flow rate through soil), m day ⁻¹
Peat-permafrost soils	0–30 cm	Loose peat (TE, 0–30 cm)	0.01–0.05
Drained gleyed soils	50–100 cm (decrease)	Sandy loam	2–3

Soil Type	Groundwater Level	Particle-Size Composition	Filtration Coefficient (water flow rate through soil), m day ⁻¹
Light-humus stratozems	0–45 cm (amplitude)	Alluvium	1–5

Upon detailed examination of drained pond and lake soils, distinct traces of reed vegetation can be observed. Thus, during the investigation of the littoral zones of Lake Bagan, common reed, *Phragmites australis*, was identified, contributing to phytolith formation and the development of a carbon framework. Alongside it, remains of fennel pondweed, *Potamogeton pectinatus*, transitioning into organic matter within alluvial layers, as well as cattail fibers filling the structure of the upper horizon, were found. However, these components account for no more than 2% of the total organic matter. Plants leave behind organic carbon, diatoms, and phytoliths. Microfauna predominates within the upper alluvial layer to a depth of 45 cm; its principal representative is the freshwater sponge spicule of *Spongilla lacustris*. The primary contribution of these organisms to pedogenesis is the accumulation of silicon dioxide. The occurrence of such microfaunal forms serves as a direct indicator of the onset of paludification in adjacent territories. The principal representatives of the macrofauna are oligochaete worms, which loosen the soil, mix peat material, and improve soil structure.

The composition of microorganisms differs depending on soil type. For example, stratozems contain plankton indicating the presence of a nearby relict lake, cyanobacteria that contribute to oxygen production and organic matter input, and fish remains contributing to organic matter transformation and humus formation from organic matter.

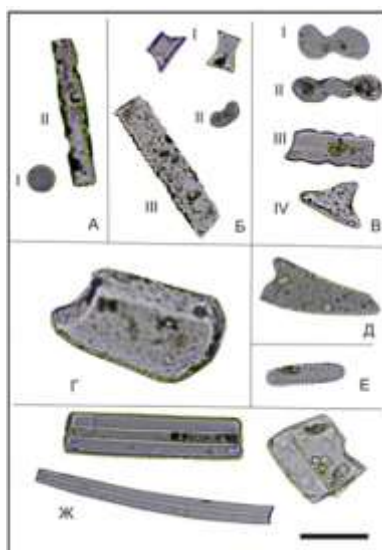


Figure 3 — Microbiomorphs: A — phytolith types common to many plants: I — spherical, II — elongated smooth; B — phytoliths of steppe grasses: I — truncated conical, II — saddle-shaped, III — elongated dentate; C — phytoliths of meadow grasses: I — bilobate, II — trapeziform polylobate, III — trapeziform undulate, IV — meadow trichome; D — phytolith of the genus *Phragmites* sp.; E — phytolith of forest grasses (forest trichome); F — diatom alga; G — sponge spicules: I — from the humus horizon of the stratozem (10 cm), II — from the stratified horizon of the stratozem (30 cm), III — from the accumulative-carbonate horizon of the stratozem (70 cm). Scale bar: 20 μ m; material adapted from [8].

In peat-permafrost soils, by contrast, anaerobic bacteria, including methanogens, as well as azotobacteria and mycorrhizae, are present. This indicates low oxygen content and an ongoing process of soil transformation. The presence of nitrogen-fixing bacteria should be regarded as a positive factor, as they contribute to the conversion of nitrogen into forms more accessible to

plants. Table 5 presents a brief summary of all organisms influencing the soil.

Table 5: Role of Biota in the Formation of Different Soil Types

Biota	Soil Type	Contribution to Structure	Organic Matter
Sponge spicules	Stratozems	Alluvial framework (0–45 cm)	SiO ₂
Common reed phytoliths	Stratozems	Fibrous structure	Corg 1–2%
Diatoms	Stratozems	Lake relics	Biogenic Si
Grasses (<i>Calamagrostis</i> spp.)	Peat-permafrost soils	TE 0–30 cm	Corg 30–40%
Mycorrhiza	Peat-permafrost soils	Organic matter depolymerization	N cycle
Methanogens	Peat-permafrost soils	Anaerobic decomposition of organic matter	CH ₄

Peat-permafrost soils of the thermokarst Lake Opytnoye basin are characterized by cryogenic pedogenesis under conditions of permafrost aggradation following natural drainage that occurred nearly 90 years ago. The profile of a typical tundra meadow includes black-brown decomposed peat merging with perennially frozen ground. “Ecosystem protection” is provided by the high thermal conductivity of ice-rich peat, which limits the deepening of the active layer and stabilizes tundra landscapes. The active layer, 0.3–1 m thick, supports the development of grass meadows dominated by *Calamagrostis purpurea*, producing raw-humus horizons with high organic carbon accumulation (Corg 30–40%).

Light-humus stratozems represent synlithogenic soils of the littoral zone of Lake Bagan, formed under unstable hydrological conditions with groundwater-level fluctuations ranging from 0 to 45 cm. The profile is characterized by a two-membered structure consisting of an alluvial layer overlying silty loam. Synlithogenesis ensures continuous alluvial input, diluting organic carbon (Corg 1–2%) and creating a bimodal distribution of particle-size fractions. The microbiomorphic spectrum, including sponge spicules, diatoms, and phytoliths, records two hydrological cycles, reflecting the sequential replacement of steppe vegetation by meadow vegetation and ultimately by reed communities. An alkaline soil reaction and the presence of a carbonate lower horizon are typical of arid steppe littoral environments with a low moisture index.

Drained gleyed soils are transformed hydromorphic soils subjected to drainage reclamation aimed at converting the water regime from anaerobic to aeration-leaching conditions. Following drainage, the upper layer becomes eluviated, below which an illuvial horizon develops, underlain by a secondarily gleyed stratum.

All listed soils possess specific characteristics presented in Table 6.

Table 6: Physicochemical Properties of Soils

Property	Peat-permafrost soils	Stratozems	Drained gleyed soils
Corg, %	30–40	1–2	1.8–2.5
pH	4.5–5.5	6.8–8.5	5.0–6.0
Bulk density, g cm ⁻³	0.8–1.0	1.2–1.4	1.2–1.4
Kf, m day ⁻¹	0.01–0.05	1–5	2–3
Structure	Cryoturbated	Stratified	Granular-aggregated

The organic matter of the soils described in the reviewed studies differs substantially in quantity, quality, the ratio of labile to stable pools, and C:N:P stoichiometry.

In peat-permafrost soils of the Lake Opytnoye basin, the content of organic carbon (Corg) reaches 30–40% within the coarse-humus peat horizon. The quality of organic matter is characterized by a moderate degree of decomposition, with *Calamagrostis purpurea* dominating the botanical composition (~70%). The C/N ratio ranges from 18 to 25, indicating a low mineralization rate and high stability of organic matter. The labile pool accounts for 20–30% (predominantly plant residues), while the stable pool comprises 70–80%. The stoichiometric ratio C:N:P is close to 100:10:1.

Light-humus stratozems of Lake Bagan are characterized by low Corg content (1–2%) due to constant dilution by alluvial sediments. Organic matter is of microbimorphic origin (sponge spicules, diatoms, phytoliths) and is represented by young labile organic material with a C/N ratio of 10–12. The labile pool (particulate organic matter, POM) constitutes 36% (alluvium and biomorphs), whereas the stable pool accounts for 64% (carbonate-associated organic matter). The C:N:P ratio of approximately 80:8:1 reflects high nitrogen availability.

In drained gleyed soils following reclamation, the Corg content in the eluviated AELu horizon decreases to 1.8–2.5% due to eluviation. The quality of organic matter transforms toward a fulvate type; the C/N ratio ranges from 8 to 10, indicating enhanced mineralizability due to aeration. The labile pool reaches 16–24%, while the stable pool concentrated within the illuvial Bt horizon comprises 76%. The stoichiometry C:N:P ≈ 60:6:1 indicates active aerobic mineralization.

The ecosystem dynamics of the pools are determined by zonal features. In the tundra zone, cryogenic conservation of stable carbon predominates; in steppe stratozems, synlithogenic lability dominates; whereas in reclaimed gleyed soils, agrotechnogenic mineralization prevails. Biotic control by earthworms and mycorrhiza regulates transformation of particulate organic matter into mineral-associated organic matter (MAOM), determining nutrient availability.

The water-air regime and redox conditions (Eh–pH profiles) of the studied soils are determined by their hydrological status, the presence of cryogenic barriers, and reclamation-induced transformations.

In peat-permafrost soils of the Lake Opytnoye basin, permafrost (depth 0.4–0.6 m) functions as a hydraulic barrier, maintaining high moisture saturation of the TE horizon (70–90%) and low aeration (less than 10% O₂). The filtration coefficient ranges from 0.01 to 0.05 m day⁻¹, with surface runoff predominating. Eh values vary from reducing conditions (100–200 mV in

depressions) to transitional conditions (300–500 mV on hummocks); pH remains stably acidic (4.5–5.5).

Light-humus stratozems of Lake Bagan are characterized by high water permeability of the alluvial AJaq horizon (K_f 1–5 m day⁻¹), ensuring good aeration. Groundwater-level fluctuations (0–45 cm) create alternating oxidative conditions (Eh 500–700 mV) during summer and weakly hydromorphic conditions (Eh 200–400 mV) during water-level rise. Water-filled pore space is 40–50%; pH is neutral to alkaline (6.8–8.5).

Drained gleyed soils following reclamation acquire an optimal aeration-leaching regime at groundwater levels of 50–100 cm and K_f values of 2–3 m day⁻¹. Aeration increases, with water-filled pore space reaching 30–40%. The Eh profile is predominantly oxidative: 400–600 mV in the AELu horizon, 300–500 mV in Bt, with relict reducing conditions in BCg (less than 200 mV). The soil reaction is slightly acidic (pH 5.0–6.0).

Seasonal Eh fluctuations are most pronounced in spring, when Eh decreases by 100–200 mV during perched water formation and stabilize in summer according to aeration status. Biogenic aeration caused by earthworm activity locally increases Eh by 50–100 mV. Optimal agronomic conditions correspond to Eh values above 400 mV at pH 5–7.

Similar saline peat-bog soils occur within the territories of the Priazovsky Nature Reserve and the “Lotos” Nature Reserve; comparable soils may also form within other protected areas and pond-farming systems. Along the southern coast, on the slopes of the Greater Caucasus Range, the subsequent developmental stage of such soils is represented by profiles with eluviated bleached layers. These include soddy-calcareous and podzolic yellow soils. Research activities on such soils are complicated by complex terrain conditions.

DISCUSSION AND CONCLUSION

The risks associated with the limited availability of ready-to-use and potentially fertile soils become particularly significant under conditions of economic instability and food-security pressure. Crop rotation systems should be assessed in advance, alongside preliminary empirical studies across the broader territories of the Bolshezemelskaya Tundra, where larger areas are available for experimental research. Nevertheless, with regard to the soil science of drained lake and pond lands, this field remains poorly developed and directly dependent on external inputs and the condition of natural pastures. Data previously obtained from other soils with less pronounced risk factors may serve as a basis for new investigations. Such experiments may influence the future of the agricultural sector and create new opportunities for agricultural production and related business niches.

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