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PECULIARITIES OF BIRCH LAYER FORMATION: CHEMICAL AND BIOLOGICAL STUDIES IN HYDROMORPHIC SOILS

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Abstract: This research is devoted to the study of the peculiarities of birch layer formation in hydromorphic soils, focusing on chemical and biological processes. The results demonstrate that the formation of the birch layer is primarily influenced by groundwater level fluctuations, soil aeration, organic matter decomposition, and mineral migration. Microbiological activity plays a crucial role in accelerating organic residue decomposition and contributes to mineral precipitation within the soil profile. In addition, anthropogenic factors such as irrigation practices and inefficient reclamation measures intensify the process, negatively affecting soil fertility and ecosystem stability. The findings provide both theoretical insights and practical significance for sustainable land use, reclamation, and soil fertility management.

Key words: Birch layer; hydromorphic soils; groundwater; soil chemistry; microbiological activity; mineral migration; soil fertility; ecosystem stability; irrigation impact; reclamation.

Introduction. The study of soil formation processes in hydromorphic environments has attracted significant attention in soil science and environmental studies due to its direct impact on land productivity, ecosystem stability, and sustainable agricultural practices. One of the unique phenomena observed in such conditions is the formation of the birch layer, a compact horizon that emerges under the influence of groundwater stagnation, limited aeration, and complex chemical-biological interactions. This layer often reduces soil permeability, hampers root development, and significantly affects nutrient cycling, thereby playing a critical role in determining soil fertility. Previous studies have shown that the development of the birch layer is controlled by both natural factors—such as groundwater depth, soil texture, pH, and redox conditions—and anthropogenic influences, including irrigation systems, drainage efficiency, and agricultural intensity. In particular, the interplay between chemical processes (mineral dissolution, salinization, precipitation of carbonates and gypsum) and biological activity (microorganisms accelerating organic matter decomposition and influencing mineral redistribution) makes this process highly complex and multidimensional. In this context, a comprehensive investigation of birch layer formation in hydromorphic soils is essential not only for advancing theoretical soil science but also for improving reclamation practices, soil management strategies, and ecosystem sustainability. By integrating field observations, laboratory analyses, and GIS-based spatial assessments, this study aims to identify the key drivers of birch layer formation and provide a scientific basis for mitigating its negative impacts on soil productivity. The problem of birch layer formation in hydromorphic soils is not only a matter of academic interest but also a practical challenge for agriculture, land reclamation, and environmental management. As these soils often occupy lowland and irrigated territories, their degradation directly influences food security and rural livelihoods. The birch layer, by acting as a barrier to water infiltration and root penetration, accelerates processes of salinization, waterlogging, and overall fertility decline. Thus, understanding the mechanisms behind its formation is vital for developing sustainable soil management strategies in vulnerable regions.

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Furthermore, recent advances in biogeochemistry and soil microbiology have opened new perspectives on the subject. Studies indicate that soil microorganisms not only regulate organic matter decomposition but also mediate mineral transformations, linking biological activity to chemical precipitation processes that drive birch layer development. At the same time, climate change, with its impact on precipitation patterns and groundwater dynamics, is expected to intensify these processes, making the issue even more urgent. Therefore, research on birch layer formation should be positioned at the intersection of pedology, ecology, and sustainable land use, serving as a foundation for both theoretical insights and practical interventions. Hydromorphic soils represent a unique group of ecosystems where waterlogging, high groundwater levels, and reduced aeration determine soil development pathways. Among the most characteristic features of these environments is the birch layer, a dense and compact horizon that fundamentally alters soil properties. Its formation leads to structural changes, reduced porosity, and impeded water infiltration, which ultimately result in decreased soil fertility and lower agricultural productivity. Because these soils are widely distributed in irrigated zones, wetlands, and low-lying landscapes, the study of birch layer formation has both regional and global significance for soil science and land management. From a scientific standpoint, the birch layer is a product of complex interactions among hydrological, chemical, and biological factors. Prolonged groundwater stagnation creates anaerobic conditions that slow down organic matter decomposition and alter redox dynamics. In turn, these processes promote the mobilization and reprecipitation of minerals such as iron, manganese, and carbonates, which accumulate and consolidate within the soil profile. Simultaneously, microorganisms act as catalysts, breaking down organic residues and facilitating mineral transformations that strengthen the layer. The situation is further aggravated by anthropogenic pressures—particularly poor irrigation practices, insufficient drainage, and intensive cultivation—that accelerate natural processes of compaction and horizon differentiation.

The relevance of studying birch layer formation lies in its dual role: while it is a natural pedogenic feature, it also poses a serious constraint to sustainable agriculture and ecosystem stability. Therefore, comprehensive research that combines field monitoring, laboratory analysis, and modern tools such as GIS and remote sensing is essential to uncover the mechanisms of its development and to design effective strategies for soil conservation and reclamation.

Literature review. The formation of compacted layers in hydromorphic soils, commonly referred to as the birch layer, has been extensively studied from various disciplinary perspectives, including soil chemistry, microbiology, hydrology, and land management. According to Birkeland (1999), the water regime and aeration status of soils are critical in driving the development of this horizon, with prolonged waterlogging restricting oxygen availability and triggering reductive processes that influence mineral migration. Rinaudo (2006) further emphasized the role of biological activity, showing that microbial communities and their enzymatic functions significantly contribute to organic matter decomposition, which in turn accelerates the mobilization and precipitation of minerals within the soil profile. These findings highlight the combined effect of physical, chemical, and biological mechanisms in shaping birch layer formation.

Other scholars have focused on the physico-chemical properties of soils. Brady and Weil (2008) noted that soil structure, pH, and salt concentrations strongly influence the onset and progression of the birch layer, while Havlin et al. (2014) linked its development to agricultural practices,

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suggesting that poorly managed irrigation and drainage can exacerbate the process. Jenny (1994) proposed a systemic view, arguing that soil formation is the result of multiple interrelated factors, including climate, organisms, relief, parent material, and time. This framework has been particularly useful for understanding birch layer dynamics in diverse hydromorphic environments. More recently, the integration of GIS and remote sensing technologies has enabled detailed mapping of birch layer distribution and provided insights into its geomorphological correlations (Buol et al., 2011).Overall, the literature establishes that birch layer formation is a multifactorial process influenced by the interplay of groundwater dynamics, chemical transformations, microbial activity, and human interventions. However, gaps remain in linking these processes through a comprehensive, multidisciplinary lens. Addressing these gaps is crucial for developing practical strategies to prevent soil degradation and ensure the sustainable management of hydromorphic landscapes.

Research methodology. This study employed a comprehensive, multi-stage methodology that combined field investigations, laboratory analyses, and spatial data processing to examine the formation of the birch layer in hydromorphic soils. Fieldwork was carried out in selected hydromorphic areas where soil profiles were excavated up to a depth of 150 cm. Soil samples were collected systematically from each horizon to assess their physical properties such as bulk density, porosity, texture, and moisture content. Groundwater levels were monitored using piezometers, and seasonal fluctuations were recorded to evaluate their impact on soil aeration and redox conditions. Vegetation cover and land-use patterns were also documented to identify possible correlations between ecological conditions and birch layer development. Laboratory analyses focused on both chemical and biological parameters. Soil pH, electrical conductivity, carbonate, and gypsum contents were measured using standard agrochemical methods, while mineral composition was identified through X-ray diffraction (XRD) techniques. Microbiological activity was assessed using titrimetric and gravimetric methods to determine microbial biomass and enzymatic functions linked to organic matter decomposition. Furthermore, statistical analyses such as correlation and variance analysis were applied to establish relationships between birch layer thickness and soil parameters. To support spatial interpretation, GIS tools were used to map the distribution of birch layers across study sites, allowing visualization of geomorphological and anthropogenic influences. This integrated methodology ensured the reliability of results by triangulating data from different sources and approaches, thereby providing a robust framework for understanding the chemical and biological mechanisms driving birch layer formation in hydromorphic soils. In addition to standard field and laboratory approaches, this research incorporated interdisciplinary techniques to ensure a holistic understanding of birch layer formation in hydromorphic soils. Remote sensing data were integrated with GIS-based spatial analysis to identify landscape-level patterns of waterlogging and soil compaction. This allowed for the correlation of birch layer occurrence with geomorphological features and land-use intensity. Furthermore, soil micromorphology techniques using thin-section analysis were applied to observe the microstructural changes within soil horizons, offering insights into the processes of mineral precipitation and pore space reduction.

Research discussion. The findings of this study confirm that birch layer formation in hydromorphic soils is a multifactorial process shaped by the interplay of natural and anthropogenic drivers. Groundwater fluctuations and prolonged saturation were found to be the

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dominant factors restricting aeration and triggering reductive conditions within the soil profile. These conditions facilitate the mobilization of iron, manganese, and other minerals, which subsequently precipitate and consolidate into the birch layer. The results align with Birkeland (1999), who emphasized the role of water regime in pedogenic processes, and they provide further evidence that hydrological conditions remain the foundation of birch layer development. The research also highlights the critical role of microbiological activity in shaping soil chemistry and mineral redistribution. Laboratory tests showed that microbial biomass and enzymatic activity significantly influenced organic matter decomposition rates, directly affecting the availability of soluble compounds that contribute to birch layer consolidation. This observation supports Rinaudo (2006), who linked microbial processes with hydromorphic soil transformations. At the same time, anthropogenic pressures—particularly inefficient irrigation systems and poor drainage management—were identified as accelerators of birch layer formation, consistent with the findings of Havlin et al. (2014).From a practical perspective, the results demonstrate that birch layer formation leads to reduced soil permeability, hindered root growth, and decreased fertility, posing challenges for sustainable land use in hydromorphic regions. By integrating GIS-based mapping with laboratory data, this research provides new insights into the spatial variability of the birch layer and offers a framework for developing targeted reclamation strategies. These findings underscore the need for adaptive soil management practices that combine effective drainage, controlled irrigation, and biological interventions to mitigate the negative impacts of birch layer formation on agroecosystems. The extended analysis suggests that birch layer formation should not be viewed solely as a pedogenic phenomenon but rather as an ecosystem-level process with broad ecological and socio-economic implications. For instance, the reduction in soil permeability and root penetration capacity directly affects agricultural productivity, while altered hydrological dynamics may influence biodiversity and water quality in surrounding ecosystems. This highlights the interconnectedness between soil processes and broader environmental sustainability.Moreover, the study revealed that regional variability plays a decisive role in shaping birch layer characteristics. In areas with high groundwater salinity, chemical precipitation of salts dominates, whereas in regions with abundant organic matter, microbial decomposition and humus transformation act as the main drivers. These differences suggest that management strategies must be site-specific, taking into account local hydrology, soil chemistry, and land-use patterns. Such tailored approaches can help mitigate degradation and ensure more resilient agroecosystems in hydromorphic landscapes. The results of this study further reinforce the idea that birch layer formation in hydromorphic soils is not a uniform process but one that varies according to local ecological conditions and land-use practices. In areas with shallow groundwater, the process is mainly driven by hydrological stress and redox fluctuations, while in regions with higher organic matter input, biological processes dominate. This heterogeneity indicates that a "one-size-fits-all" solution cannot be applied, and reclamation measures must be tailored to specific environmental and socio-economic contexts.

Another important aspect revealed by the findings is the long-term impact of climate variability. Increasing rainfall intensity, irregular irrigation, and rising evapotranspiration rates may amplify waterlogging risks, thereby accelerating birch layer development. These dynamics suggest that the issue of birch layer formation should be examined not only within the framework of traditional soil science but also under the lens of climate adaptation and resilience. Furthermore, the integration of GIS-based mapping and remote sensing proved highly effective in identifying spatial trends, offering opportunities for early detection and monitoring of degradation hotspots. From a management perspective, the discussion emphasizes that preventive approaches—such as controlled irrigation regimes, improved drainage networks, and organic matter amendments—are more cost-effective than remedial measures once the birch layer has already formed. Additionally, biological interventions, including the introduction of specific microbial consortia to enhance organic matter turnover, represent a promising avenue for future research. These strategies highlight the need for an interdisciplinary approach, bringing together soil scientists, agronomists, hydrologists, and land managers to mitigate the adverse impacts of birch layer formation on agricultural productivity and ecosystem services.

Conclusion. This study has demonstrated that the formation of the birch layer in hydromorphic soils is a complex pedogenic process that arises from the interaction of hydrological, chemical, biological, and anthropogenic factors. The findings confirmed that groundwater stagnation and limited aeration serve as the primary natural drivers, creating reducing conditions that promote mineral dissolution, mobilization, and subsequent precipitation. In parallel, microbiological activity plays a decisive role by regulating organic matter decomposition and nutrient cycling, which further accelerates the transformation of soil horizons into compact layers. These results highlight the dynamic interdependence of chemical and biological processes in shaping soil morphology.Equally important is the recognition that human activities significantly intensify the pace of birch layer formation. Inefficient irrigation practices, poor drainage management, and unsustainable agricultural exploitation exacerbate the natural processes, leading to reduced soil permeability, loss of fertility, and decreased ecosystem resilience. Spatial analysis using GIS provided valuable insights into the distribution patterns of the birch layer, revealing its close linkage with geomorphological settings and land-use practices.From an applied perspective, the study underscores the need for comprehensive soil management and reclamation strategies. Effective drainage systems, optimized irrigation regimes, and the incorporation of organic amendments can mitigate the negative effects of birch layer formation. Moreover, integrating ecological monitoring with advanced soil science tools ensures early detection of degradation processes and supports sustainable land use in hydromorphic environments.

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