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Review

Paludiculture in Latvia—Existing Knowledge and Challenges

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Abstract: Global climate change impact has increased in recent decades and put urgency on implementing effective climate change mitigation (CCM) activities. Rewetting of drained peatlands is an acknowledged measure to reduce GHG emissions from organic soils in the agriculture and land use sectors. Under waterlogged conditions, decomposition of organic matter in peat decreases, and emissions of CO_2 are reduced. Thus, the soil carbon stock is saved, and wet management of the site reactivates carbon sequestration. To reach CCM targets, the first rewetting and paludiculture trials have been implemented in Latvia. In this article, we review the current status of paludiculture in Latvia and evaluate the pros and cons of their wider implementation. The majority of paludiculture projects and pilot studies in Latvia have not been published so far and are reported here for the first time. Our assessment of paludiculture shows that trails on *Alnus*, *Phalaris*, *Phragmites*, *Sphagnum*, and *Typha* installed by the private enterprises have promising results for upcoming large-scale implementation. There are available areas for paludiculture in Latvia, but the current legislation and national framework policies (environment, agriculture, forest, and climate) do not fully support such activities yet and must be adapted.

Keywords: organic soils; peatland; peat; carbon credits; agriculture; forestry

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1. Introduction

Following the Paris Agreement, climate neutrality must be achieved by 2050. There are multiple approaches to accomplish this, and a significant recommendation from CAP (Common Agricultural Policy) is to rewet organic soils and peatlands. This involves reducing the harvesting of peat and minimizing the usage of drained peatlands for agricultural and forestry purposes. Additionally, it is crucial to explore opportunities to utilize cutover peat areas and unproductive organic soils, which are not suitable for conventional agriculture and/or forestry, in order to achieve climate and biodiversity objectives [1]. Rewetting of organic soils and peatland areas to ensure climate and economically friendly usage is thought to be paludiculture.

Paludiculture is agriculture and forestry on wet and rewetted organic soils and peatlands [2]. Agroecological principles and practices, ecosystem-based management, and other approaches that work with natural processes support food security, nutrition, health and well-being, livelihoods and biodiversity, sustainability, and ecosystem services. These services include not only buffering of temperature extremes but also carbon sequestration and long-term storage, which enhances the resilience of carbon stocks and sinks [3].

Latvia is located in north-eastern Europe, within the hemiboreal zone where precipitation exceeds evaporation, thus allowing for peat formation and accumulation. Peatland comprises nearly 10–12% of the territory of Latvia [4]. Holocene peatland formation in

Latvia dates to more than 11,000 years ago [5]. Peat extraction for private households increased dramatically during industrialization with melioration schemes for land reclamation in agriculture and forestry. Melioration efforts peaked in the Soviet occupation period in the 1960s–1970s when the fields for energy peat production were drained on a large scale. Later, excavation of substrate peat was implemented in sites where exploitable white peat deposits prevailed [6]. Today, the global substrate peat market has depleted exploitable white peat resources in Western Europe and keeps pressure on the Baltic peat industry for the production of high-quality peat substrates for professional horticulture and tree nurseries. To meet the demand for substrates, 0.04% of the territory of Latvia (or 4% of the peatland area) is used for peat extraction.

The aim of this study is to review and evaluate experience from eight sites in Latvia in order to raise awareness of the strengths and weaknesses of paludiculture implementation and to provide advice for best practices.

2. Materials and Methods

Paludiculture is the agricultural or silvicultural use of wet and rewetted peatlands. Paludiculture uses spontaneously grown or cultivated biomass from wet peatlands under conditions in which the peat is conserved or even newly formed [7]. Rewetting of drained peatlands and use with close-to-surface groundwater levels (paludiculture) could reduce emissions and considerably contribute to reaching Latvia's climate mitigation targets.

There is a wide array of defined paludiculture taxa and species [8]. In this paper, we focus on selected paludiculture species that grow and are cultivated for use in Latvia (Figure 1). Taxa in question comprise peat moss (*Sphagnum* spp.), black alder (*Alnus glutinosa*), reed (*Phragmites australis*), reed canary grass (*Phalaris arundinaceae*), cattail (*Typha latifolia*/*angustifolia*), sweet flag (*Acorus calamus*), and wet meadows. We gathered available published information on applied practices and reached out to private enterprises to determine their practices and, when possible, operational costs for the implementation of paludiculture. We then proofed and discussed the compatibility of applied approaches with paludiculture standards.

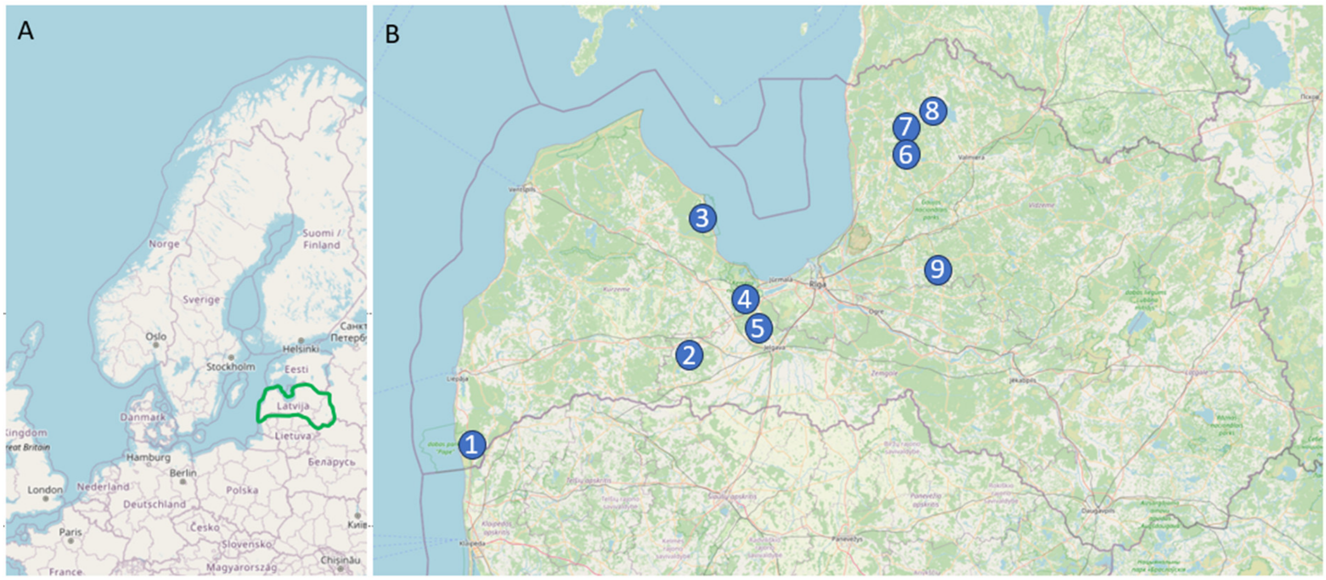

Figure 1. Location of Latvia within northern Europe (**A**). Location of paludiculture implementation and cultivation sites discussed in the text: (1) Nida (*Phragmites*); (2) Lake Svetes vicinity (*Alnus glutinosa*); (3) Engure (*Phragmites*); (4) Ķemeri Bog (*Sphagnum*); (5) Kaigu Bog (*Sphagnum*); (6) Rāķa Bog (*Sphagnum*); (7) Tēvgāršas Bog (*Typha*); (8) Rūja River floofplain valley (*Phalaris*); (9) Ķēviešu Bog (*Sphagnum*) (**B**).

3. Results

According to the results of the LIFE Restore project it has been determined that approximately 50,000 hectares of land in Latvia have been impacted by peat extraction activities. Among these, around 15,000 hectares are presently active peat extraction sites, while reclamation efforts have been undertaken or are currently in progress on approximately 17,000 hectares of land. Notably, there are approximately 18,000 hectares (equivalent to 36% of the total) that represent abandoned cutaway peatlands requiring reclamation efforts.

For a visual overview of the current and potential utilization of organic peat soils in Latvia, encompassing forestry, agriculture, and peat extraction, please refer to Figure 2. The management of these peat soils involves a combination of drainage and rewetting methods, which encompass both natural-origin and artificially established sites. Drained peat soils with a sphagnum peat layer have traditionally found use primarily in berry cultivation, afforestation, and peat extraction. However, these versatile landscapes also offer opportunities for more sustainable and ecologically conscious practices, such as establishing bee pastures adorned with flora like heather and wild rosemary, which can be harmoniously combined with renewable energy sources like solar panels or windmills.

Organic soils, whether drained or undrained and rich in black or white peat, hold significant potential for the implementation of wind farms and agrovoltaics—solar farming, is an innovative and sustainable land-use practice that combines agriculture with the generation of solar energy. Agrovoltaics maximizes land utilization by effectively using the same space for both agricultural production and solar energy generation. Solar panels can provide shade to crops, reducing the risk of heat stress and excessive evaporation, which can be particularly valuable in areas facing water scarcity or drought conditions, including extracted bare peat fields. Solar panels can be placed above cranberry fields. The shading effect can help manage water temperatures, reduce water usage, and improve cranberry yields. The space under solar panels can be managed to support biodiversity, creating habitats for pollinators and wildlife, e.g., bee pastures covered with heather and wild rosemary. Agrivoltaics is a novel concept in Latvia, and as a result, its potential impact on biodiversity as yet to be thoroughly investigated.

Rewetted peatlands, whether enriched with raised bog or transitional mire peat, provide a diverse landscape for ecological restoration and sustainable land utilization:

- rewetted peatlands play a pivotal role in the restoration of degraded ecosystems, promoting the growth of sphagnum mosses and the revitalization of peatland habitats. This restoration effort fosters biodiversity and supports the revival of native flora and fauna;
- these landscapes are well-suited for berry cultivation, including cranberries, lingonberries, and blueberries. Additionally, rewetted peatlands can be utilized for bee pastures and the cultivation of medicinal plants, such as marsh trefoil, sweet flag, sweet gale, and meadowsweet;
- drained sites with a black peat layer, once associated with agriculture and peat extraction, hold promising potential for renewable energy production. Transforming these areas into wind or solar parks can harness clean energy resources while reclaiming previously exploited land for sustainable purposes;
- rewetted peatlands are suitable for wet agriculture practices, including the cultivation of wetland plants like cattail, sedges, and rush. Moreover, these areas offer an ideal environment for growing willow and black chokeberry, both of which can serve as valuable crops. Furthermore, the concept of agrovoltaics can be employed, emphasizing the synergy between wet agriculture and solar energy generation. Solar panels can be integrated into the landscape to complement agricultural activities, promoting sustainable and renewable energy practices in wetland settings;
- rewetted sites can also be used for ornamental plant cultivation, and native plant species can be reintroduced to bolster local biodiversity.

Figure 2. Management of degraded peat soils in Latvia.

Rewetted peatlands, whether in the context of ecological restoration, agriculture, renewable energy, or agrovoltaics, offer a multitude of opportunities to harmonize human activities with the preservation of peatland ecosystems.

3.1. *Sphagnum spp. Moss*

In raised bogs, peat formation predominantly occurs under nutrient-poor, acidic conditions, largely due to peat mosses, specifically *Sphagnum* spp., which are well-adapted to these environments. Peat moss has a unique ability to acidify its environment using hydronium ions and creates self-regulating structures to maintain consistently high water levels. As a result of these unique conditions, layers of undecomposed and slightly decomposed peat moss accumulate, reaching depths of several meters. This type of peat, often referred to as "white peat" because of its light color, boasts properties like high porosity, low nutrient content, and a uniform fibrous structure, making it a crucial raw material for professional horticultural substrates globally. Today, nearly all vegetable and decorative plants and flowers are potted in substrates derived from white peat.

The horticultural sector, along with scientific communities, is proactively seeking alternatives to moss peat for horticultural substrates. However, potential substitutes like alternative biomass and artificial substrates often pose challenges in production costs and inconsistency in properties compared to white peat. Studies from Canada and Germany indicate that fresh peat moss biomass shares properties with white peat and can serve as an effective substitute in horticultural substrate production [9,10].

Moreover, cultivating *Sphagnum* moss, termed "*Sphagnum* farming", has been found to be beneficial for peatland restoration in areas previously used for peat harvest and adjacent to current peat extraction sites. Such restorative efforts can significantly contribute to the ecological balance in peatland ecosystems, prioritizing both biodiversity and climate objectives. Cultivated *Sphagnum* moss can be harvested in intervals of 3 to 5 years.

In Latvia, efforts have been made to cultivate *Sphagnum* at four distinct sites. The first *Sphagnum* farming experiment began in 2012 at the Mokura Europe Ltd-owned Ķēviešu Bog (Figure 1), spearheaded by the Greifswald University and Greifswald Mire Centre. Later, in 2016, the Lake and Peatland Research Centre, aided by scientists and volunteers, initiated *Sphagnum* planting at Kaigu Bog, within Laflora Ltd.'s peat extraction fields (Figure 3). Subsequently, in 2018, the LIFE Restore project planted *Sphagnum* in a 0.45 ha area of Ķemeri National Park for restoration purposes. Concurrently, Klasmann-Deilmann Latvia Ltd. began cultivating *Sphagnum* in their Rāķa Bog extracted peat fields, encompassing a 0.7 ha area, with additional water basins extending it to 1 ha. The company has summarized the installation and planting costs, and they are compared with the installation costs of the 0.45 ha *Sphagnum* field in Ķemeru Bog (Table 1). The total cost per hectare in Rāķa Bog was EUR 38,540, excluding project-related expenses. In contrast, the cost in Ķemeru Bog was EUR 32,300 per hectare, with the project expenses also not included.

The Rāķa Bog stands out with its extensive water management infrastructure, which includes pumps and pools and constitutes a significant portion of the project's expenses. Rāķa Bog has a comprehensive water management system, with the most significant expense being the water pool at EUR 8491. The overall cost for water management in Rāķa Bog was EUR 12,701. Meanwhile, Ķemeru Bog only had the construction of an overflow and depressions installed, costing EUR 1530.

Located in a private, secured area, the Rāķa Bog benefits from the surrounding active peat extraction fields, ensuring equipment security and consistent water level monitoring. Contrastingly, the *Sphagnum* field in Ķemeru Bog borders a frequented tourist path. Both locations lack a permanent electrical connection, and as necessary, water pumps operate using diesel generators.

All three bogs experience water level reductions during summer. However, in Rāķa Bog, water shortages are mitigated using water basins. One with acid water, another more distant with alkaline water. Groundwater from a second basin becomes necessary during peak dry periods. This leads to higher concentrations of nutrients in the irrigation water.

While the closest basin can supply water to areas already planted with *Sphagnum* in Rāķa Bog, expanding the area would require a new basin. Thus, when calculating costs per hectare, the water basin is accounted for in both the expenses and the area.

Meanwhile, in the initial phase, the irrigation system at Kaigu bog was not fully functional, and *Sphagnum* was not provided with sufficient water or even overflooded during the spring and autumn, which could have restricted *Sphagnum* growth during the initial phase or even damaged the *Sphagnum* beyond recovery. High water level fluctuations were one of the reasons (but not the only factor) for the poor establishment of *Sphagnum* moss at Kaigu bog. Moss species were severely damaged, and the area was overtaken by reed (*Phragmites australis*) and cattail (*Typha latifolia*/*angustifolia*). To ensure appropriate water quality, it is either necessary to collect only rainwater in basins or to ensure that water, before entering the basin, is filtered through peat extraction fields, natural peatlands, or peatland forests, as is the case in Rāķa Bog. This is highly important for the territory of Latvia, where sediment underlying peat layers commonly contain carbonates and groundwaters are nutrient-rich. The management of groundwater and surface water to restore *Sphagnum*-dominated habitats and irrigation of *Sphagnum* farms should focus on lowering alkalinity levels (including pH) [11]. The input of solutes from minerotrophic water may indirectly hamper *Sphagnum* growth by stimulating the growth of vascular plants, triggering unwanted vegetation shifts.

Figure 3. Sphagnum moss spreading and planting carried out by the Lake and Peatland Research Centre in the Ltd. Laflora peat extraction field in Kaigu Bog in 2016. Photo: I. Grudzinska.

Table 1. Installation and planting costs for *Sphagnum* fields in Rāķa Bog and Ķemeru Bog (LIFE Restore project).

	Rāķa Bog 0.7 ha + 0.3 ha Water Basin	**Ķemeru Bog 0.45 ha**
Position	**Costs, EUR**	**Costs, EUR**
Planning		
Topography	550	-
Project	1658	4666
Site preparation		
Marking the boundaries of the road and the planting area	-	223
Removing overgrowth	-	551
Pumping water out of a cart ditch	-	150
Digging strains and cleaning from mineral soil	8116	-
Leveling	2197	4112
Smoothing and poldering	3937	-
Shaping and compacting causeways	1642	-
Creating a pile from displaced peat	-	1543
Irrigation ditches along the causeways	220	-
Irrigation ditches in the field	1083	-
Water outlet	172	-
Water management		
Water level regulation (monk)	2795	-
Mobile pump (as required)	116	-
Water pool	9790	-
Construction of an overflow and depressions (for sediment capture)	-	1530
Planting		
Collecting moss in the donor area, transport to the field, loading/off-loading	3744	3724 2270 kg
Spreading (manually) of moss material	1380	- voluntary
Straw purchase and transport to the site	-	246 (453 kg)
Materials (footbridges, fencing, etc.)	2781	2456
Total	40,181	19,201

Visually, moss growth in Rāķa Bog appears to be more vigorous compared to that in Ķemeru Bog. Furthermore, during dry periods, the water level in Rāķa Bog remains significantly higher than in the Ķemeri site. The thickest moss layer is found in Kēviešu Bog, where planting occurred as early as 2012. However, because this site is also influenced by alkaline groundwaters, moss growth is slower than anticipated. Whether the slightly larger expenditure on Rāķa Bog provides proportionally better outcomes compared to Ķemeru Bog would need further operational and ecological data. Although maintaining a steady water supply is important, it is essential to recognize that each bog has unique characteristics impacting moss cultivation and field management. These differences are further reflected in the distinct costs associated with each field (Table 1).

An additional crucial factor for the successful establishment and growth of *Sphagnum* is the thickness of the peat layer. Regions with excessively thin peat layers can present challenges for *Sphagnum* farming, and the type of peat also plays a significant role. Leaving a thicker peat layer intact after extraction creates favorable conditions, resembling natural peatland properties, and supports both *Sphagnum* farming and raised bog ecosystem restoration. When dealing with remaining fen peat (also known as "black peat"), issues can arise due to its high degree of decomposition and higher pH, affecting subsequent peat properties for *Sphagnum* farming. For optimal growth, *Sphagnum* thrives on top of *Sphagnum* peat (often referred to as "white peat"), which is low to moderately decomposed and has a peat layer thickness exceeding 1 m [12]. Unfortunately, the lack of sufficient "white peat", together with fluctuating water levels has resulted in the termination of *Sphagnum* growth in Kaigu Bog extracted peat fields, with reeds now dominating the area.

Engaging in *Sphagnum* farming necessitates the preservation of a white peat layer; this means that the peat extractor does not generate income from the remaining peat layer. It is important to highlight that revenue projections remain indeterminate as the moss layers are yet to mature, and none of the four *Sphagnum* fields have experienced a harvest yet.

3.2. *Phragmites australis*

Common reed (*Phragmites australis*) is a tall, thin, highly productive grass that can be found in wetlands. Reed produces high and stable yields on wet sites, even with long-term flooding. Reed grows up to four meters high and remains upright after the growing season, making it suitable for harvesting in winter. Reed yield ranges from 4 to 24 t DM/ha annually. The primary production of *Phragmites* is very high, up to 10 kg dry mass per m^2 [13]. Reed is often the first peat-building species in peatlands that originated from alkaline lakes or wetland depressions.

No artificial reed fields have been established in Latvia so far, and therefore, no comparable detailed costs for *Sphagnum* farming can be provided. Latvia has 116 natural and artificial water bodies with water reservoirs (~13,400 ha in total) considered important for reed production [14]. Several Natura 2000 sites are managed for reed cutting. For example, in Lake Pape, reed is cut by six companies in an area of approximately 900 ha. Royal Reed Ltd., Rucava, Latvia, leases 600 ha and exports 300,000 bales per year, or around 12,600 t of dry matter, to Denmark, Germany, and the Netherlands. Nowadays, reed is usually preferred to straw as thatching material because of its better availability and the longer durability of the thatched roofs, with 50–60 years for common reed. Reeds are used not only as roofing material, construction and insulation boards, and ornamental and protective mats (e.g., to protect trees in urban areas) but also to replace plastic straws with natural straws.

The economical use of reed is hampered by the issues related to harvesting, transport, and drying. Dry reeds have a low density (200 kg/m^3 [14]), so transporting reeds over longer distances may not be cost-efficient. During the cold season, reed canes decrease in moisture content, but in recent years, when Latvia has had warm and wet winters, the moisture content has been higher (>20%). The rewetting of large areas may reduce the conflicts with nature conservation aims and restrictions (bird migration and nesting time in natural reed areas). Independent reed fields developed on rewetted cutover peatlands could theoretically allow the operation to run efficiently. Large-scale harvesting machinery can be used, reducing production costs. Unlike natural reed harvesting in reservoirs, reed cultivation on rewetted organic soils and wetlands would significantly reduce the cost of reed cutting and collection from EUR 500 ha^{-1} to EUR 85 ha^{-1} [15].

3.3. *Typha*

As a pioneering species of wet and muddy land, it grows well in restored peatlands and rapidly forms a dense plant cover. Cattail is suitable as a cultivation crop because it produces very high yields on rewetted sites with a high nutrient supply, even in the case of long-term overflooding. Importantly, planted cattail yields are stable over the first ten years [7]. The high productivity of the plant, and the excellent properties for insulation, construction, and fiber materials in connection with the growing demand, especially for ecological building materials, offer versatile potential for creating regional value. Growing areas can be up to 10 ha in size with high nutrient and water availability (in summer, −10–0 cm and in winter, −5–15 cm from the surface). Yield ranges from 4 to 22 t DM ha annually [8]. Projected long-term site emissions are 6–7 t CO_2-eq./ha/annually. Plants like *Typha* that bind large volumes of CO_2 due to their fast growth can be successfully implemented for carbon capture farming. If *Typha* is used to produce high-quality materials, then the carbon can be stored for the lifetime of the products. Otherwise, the annual biomass from *Typha* is decomposed rather fast, and the captured carbon is emitted back to the carbon cycle.

In Latvia, cattail grows naturally in wetlands and on the shores of lakes, but extensive areas covered with cattail are not known. In farmland, cattail is considered an undesirable plant because it indicates that the area is unkempt. However, in lakes, they are considered, like reeds, to be an indicator of heavy overgrowth. In peat extraction sites, cattail grows in ditches, and its seeds are actively restricted/prevented (i.e., cattail is eliminated) from entering the peat. Both these processes show that cattail establish and grow well on farmland and constructed marshes if allowed. The density of cattail is low (65 kg/m^3); thus, transporting cattail over long distances may not be worthwhile and costly. The productivity of cattail can range from 5 to 22 t DM ha^{-1} [8].

The first trial of a cattail field was implemented by the Lake and Peatland Research Centre in 2020 at the Tēvgaršas Bog managed by Klasmann-Deilman. The field (size 0.3 ha) was prepared on a former peat extraction site further from the current extraction fields. Total costs for the cattail farming trial field establishment were EUR 1900 (price shows surface preparation and leveling of land). Planting material was obtained from nearby ditches, and planted manually one plant per m^2. The company aimed to test such a trial to evaluate its potential as a recultivation measure and usage of the above biomass. After one year of planting, cattail was successfully spread throughout the field. Further evaluation and measurements are in progress and will be monitored by the Lake and Peatland Research Centre. As this was a scientific experiment to determine whether *Typha* establishes after installation, no additional costs were allocated in the current project. Based on this trial, a decent (like the *Sphagnum* farming project in Rāķa Bog) cost categorization will be designed for the upcoming *Typha* plantation project in the near future.

3.4. *Alnus glutinosa*

Black alder (*Alnus glutinosa*) is a scattered and widespread species that thrives in low-laying wet and riparian areas. Growth rates are up to ages 7–10, with a maximum rotation of 60–70 years for growing timber if heart rot is avoided [16]. Many strong, vertically growing sinker roots anchor the tree, and they can penetrate deeply into wet and anaerobic soils. Black alder can grow in a wide range of soils of varying nutrient status, growing equally well in acidic and basic soils, with a large range of pH values between 4.2 and 7.5. High water levels are essential when considering the utilization options in short rotation coppices or high-quality timber production. A newly established black alder plantation has a slight net (GHG in CO_2-eq.) sink of -3.4 ± 1.7 t ha^{-1} yr^{-1} [17]. The GHG balances of formerly drained fens benefit in the short term from planting black alders, mostly due to reduced CH_4 emissions. Additionally, black alder is capable of forming peat under wet and very wet conditions.

Latvia's forests cover 3.383 million hectares and 52% of the country's territory. According to the State Forest Register data, black alder stands occupied 92,869 ha in 2016, which increased to 104,418 ha by 2022 [18]. Notably, half of the black alder forests are under state ownership, while the other half are privately owned. During 2021, a total of 336 ha of alder trees were planted, while 1383 ha were regenerated naturally.

Although the black alder is a well-known and valuable tree in Latvia, targeted plantations are rare. One such plantation, spanning 4 hectares and consisting of planted black alder (located near Svete Lake, Dobele Municipality), was established on a 1.0–1.5 m thick fen peat layer in 2019 (Figure 4). This plantation was established by a private landowner. The costs per hectare include seedlings (EUR 700), heap preparation (EUR 500), planting

(EUR 170), and cleaning (EUR 300). The expenses for planting, as well as the initial three years of maintenance and cleaning costs, were financed through an EU project managed by the Rural Development Service as part of the application for the activity "Investments to expand forest areas and improve forest viability".

Figure 4. *Alnus glutinosa* plantation (fourth year after tree installation) in central Latvia. Photo: I. Ozola, 2023.

In general, the average cost of preparing, planting, and maintaining a black alder forest, depending on the quality of the forest land, ranges from EUR 2300 to EUR 2700. The revenue is EUR 13,000 per hectare for normal-quality trees and EUR 23,200 per hectare for good-quality trees.

3.5. Phalaris arundinaceae

Reed canary grass can grow in wet conditions, but its robust root system enables it to endure drier growing periods. This grass species can tolerate prolonged flooding, making it suitable for mowing lawns in areas where adequate drainage is not feasible. Moreover, reed canary grass serves as an effective means of soil protection against water erosion [19].

In Latvia, reed canary grass (*Phalaris arundinacea*) has shown successful cultivation. Both natural stands and established crops of this grass are primarily utilized as fodder for hay and silage. Once a stand is well-established, reed canary grass can thrive at a single site for 10–12 years, maintaining consistent biomass yields. Moreover, it holds the distinction of being the only paludiculture crop eligible for direct payments due to its classification as an agricultural crop. Recently, Latvia has experienced a decline in reed canary grass production, decreasing from 1160 ha in 2016 to 128 ha in 2022, as reported by the Rural Support Service [20]. This decline could be attributed to reed canary grass being mixed with other grasses, forming part of the perennial grasslands that encompassed 457,303 ha in 2021 and expanded to 461,357 ha in 2022. Reed canary grass grassland is classified as permanent grassland. Permanent grassland is land on which grasses or other forage grasses are sown or grown in the current year and on which naturally established (self-sown) or cultivated (sown) grasses or reed canary grass EU grassland habitats or bird habitats shall also be declared as permanent grassland [21].

Reed canary grass biomass is one of the alternative resources used for pellet production in the Baltics due to its sustainability in local climatic conditions and high biomass yield of 7.9–13.2 t ha^{-1}. It is an environmentally friendly source of energy that reduces energy dependence on other countries and can be grown on land that is not suitable for cereal production. In order to recultivate the former peat extraction field, the Lake and Peatland Research Centre is currently implementing a reed canary grass field on 16.4 ha at Kaigu Bog (Laflora Ltd., Kaigu Peat Bog, Latvia). Aboveground biomass will be harvested and used for pellet production. It is not only economically reasonable but also good for the climate as the reed canary grass field is a sink for atmospheric CO_2 (GWP of −11 t CO_2-eq. ha^{-1} yr^{-1}) [22]. Once the reed canary grass is planted, climate benefits can only occur in the avoidance of emissions from peat degradation by ensuring the management of close-to-surface water levels. Although there are not enough data available to comprise a sound overview of paludiculture GHG, it is important to underline at least potential GHG regarding climate scope (Table 2). These numbers must be looked at with caution as there is a lack of long-term monitoring to determine a reliable prognosis of GHG fluxes from paludiculture sites. In future research, it is important to compare alternative scenarios under drained conditions with the high emissions of GHG from peat degradation. In addition, the differentiation of carbon stocks (aboveground, root biomass, accumulation of new peat layers, etc.) and global warming potential should be included in consideration of a long-term perspective.

Table 2. Greenhouse gas emissions within the associated paludiculture species from the literature.

	CO_2	CH_4	Net CO_2eq	Reference
Sphagnum moss	Capture 6.29 t/ha	Emit 0.014 t/ha	5.94	[23,24]
Alnus glutinosa	Capture 3.5 t/ha	Emit 0.067 t/ha	1.825	[17]
Reed canary grass Phalaris	Capture 3.8 t/ha	Emit 0.01 t/ha	3.55	[25,26]
Phragmites australis	Capture 8.94 t/ha	Emit 0.3 t/ha	1.44	[27]

3.6. Acorus calamus and Iris pseudoacorus

Sweet flag (*Acorus calamus*) and yellow flag (*Iris pseudoacorus*) are often found on lakeshores and wetlands. They are often cultivated as ornamental plants in water gardens or near ponds in Latvia but can also be used as food. Furthermore, they are widely used in modern herbal medicine as aromatic stimulants and mild tonics. Yellow flag can serve as a substitute for coffee, provided it is well roasted [8]. Moreover, holding a slice of its root against a painful tooth is believed to offer instant relief. The flowers yield a lovely yellow dye. Furthermore, yellow flag has been utilized as a rehabilitation plant to reduce bacterial loads, absorb heavy metals from contaminated water, and aid in erosion control. The leaves are used in basket making or woven into mats and can be used for roof thatching. The essential oil from the leaves and the roots is an insect repellent and insecticide [8].

In 2019, the Lake and Peatland Research Centre, together with Laflora Ltd., agreed to test whether these plants can grow on a cutaway peatland with variable water levels. Three hundred tree seedlings were planted. The price per plant was EUR 1.5. Costs for the field preparation were not estimated as these fall within the *Sphagnum* trial field preparation costs (presented earlier). Neither cost of labor was estimated. The first results show that the plants were well established in 2020–2022, healthy and producing new offspring. In 2023, common reed aggressively took over the field, but after the move, both sweet flag and yellow flag regenerated and grew alongside the common reed. The plan is to harvest the plant's aboveground biomass and develop extract for medical purposes and new innovative products. Management of common reed and other potential plants should be considered further to maintain reliable growing conditions in the sweet flag field.

3.7. Wet Meadows

Wet meadows are transitional habitats between aquatic and terrestrial environments. Their waterlogged soils, diverse plant communities, and periodic flooding make them unique ecosystems that support a wide variety of flora and fauna. In Latvia, wet meadows (Figure 5) have gained attention due to their potential for paludiculture: the cultivation of wet and peaty areas for biomass production.

Figure 5. Wet meadow with dominance of reed canary grass, Rūja River floodplain, Natura 2000. Photo: I. Ozola, 2023.

Wet meadows are rich in biodiversity, supporting a wide variety of plants, birds, amphibians, and insects. Beyond this biodiversity, wet meadows on organic soils offer several other benefits. They function as natural sponges, absorbing excess water during wet periods and releasing it in drier times. They also assist in water purification, minimizing nutrient runoff into nearby water bodies and enhancing drought resilience. As noted by local farmers, during dry spells, wet meadows prove vital for cattle and other livestock by providing an alternative feed source. Furthermore, wet meadows contribute to carbon sequestration, aiding in the mitigation of climate change impacts.

Climate change poses both threats and opportunities for wet meadows. Changes in precipitation patterns and rising temperatures can alter the hydrology of these meadows, influencing their ecology and potential uses. However, the extended growing season has given landowners in the Ruja River valley a chance to mow the hay twice, in July and September.

This article highlights the Rūja River floodplain as a positive example of wet meadow management. The nature reserve "Rūja River floodplain" was established in 2004 and is located in the Valmiera Municipality. The 444 ha nature reserve is part of the North Vidzeme Biosphere Reserve. The nature management plan of the nature reserve Rūja River floodplain was developed within the LIFE-Nature project "Restoration of Latvian floodplain meadows for conservation of EU priority species and habitats" implemented by the Latvian Fund for Nature in 2006. The main aim of the reserve is to preserve rare biotopes and species in Latvia and Europe, especially the river floodplain meadows and the nesting great snipe (*Gallinago media*).

A total of 95 bird species have been recorded in the nature reserve, 26 of which are specially protected. Most of the nature reserve is agricultural land, less forest land and scrub and flowing waters. Most of the nature reserve belongs to private landowners. Most of the meadows in the nature reserve are classified by the Rural Support Service as biologically valuable meadows for which late mowing (from 1 July) or extensive grazing is preferable. This is necessary to promote the conservation of grassland and bird species. Meadow managers in the area can apply for and receive subsidies under the agri-environment and climate sub-programme of the Field Support Service for maintaining biodiversity in grasslands and Natura 2000 site status [28].

The natural values in the nature reserve and in the wider area have been negatively affected by land reclamation and river straightening. Reclamation contributes to faster water outflow, resulting in a more rapid drop in water levels in the meadows during floods. This contributes to the overgrowth of the meadows. The maintenance of certain drainage ditches is acceptable from the point of view of nature conservation. In order to avoid landowners having to maintain ditches in their ownership, they should first be removed from the drainage register, as according to the conditions of the Good Management Practice of the Rural Support Service, drainage systems should be kept in working order, which in Natura 2000 sites is inherently contrary to the conditions necessary for the conservation of natural values in floodplain meadows. The creation of dykes on ditches or the filling in of ditches is also permitted [28].

This article highlights the Rūja River floodplain as a positive example of wet meadow management. Mr.Mareks Bērziņš, the proprietor of farm z/s Lojas and manager of a 50-hectare area, stands out among local farmers. A decade ago, when he embarked on cultivating this expanse, it was predominantly overrun by reed canary grass. However, a noticeable transformation has occurred over the years, with biodiversity flourishing as the reed canary grass receded, making room for other plant species, which now constitute approximately 15% of the area.

The management of wet peat soils is a common practice in Latvia, where many farmers are actively introducing non-native plant species diverging from the typical fen vegetation. Multiple seed mixtures have been developed specifically for peaty and organic soils, designed to withstand adverse conditions and thrive in such environments, e.g., alsike clover (*Trifolium hybridum* L.), Timothy (*Phleum pratense* L.), meadow fescue (*Festuca pratensis* Huds.), tall fescue (*Festuca arundinacea* Schreb.), and perennial ryegrass (*Lolium perenne* L.) [8].

4. Discussion

Based on recent estimates [29], there are more than 111,390 ha suitable for paludiculture implementation on organic soils. Fully suitable areas after careful consideration of restrictions comprise 65,781 ha, and conditionally suitable areas after consideration of major restrictions are 142,936 ha (Figure 6). Meanwhile, areas not suitable for paludiculture constitute more than 194,684 ha, which includes mostly protected areas. In total, more than 514,791 ha of organic soil and peatland were investigated and classified based on the readiness for paludiculture and rewetting actions. Paludiculture comes into view as a feasible way to support the cutting of CO_2 emissions from drained peatlands while providing an alternative income option for local farmers. Additionally, the Baltic states' energy-security gains another decentral source of domestic electrical and heat energy, beneficial especially in remote regions with weak infrastructural development.

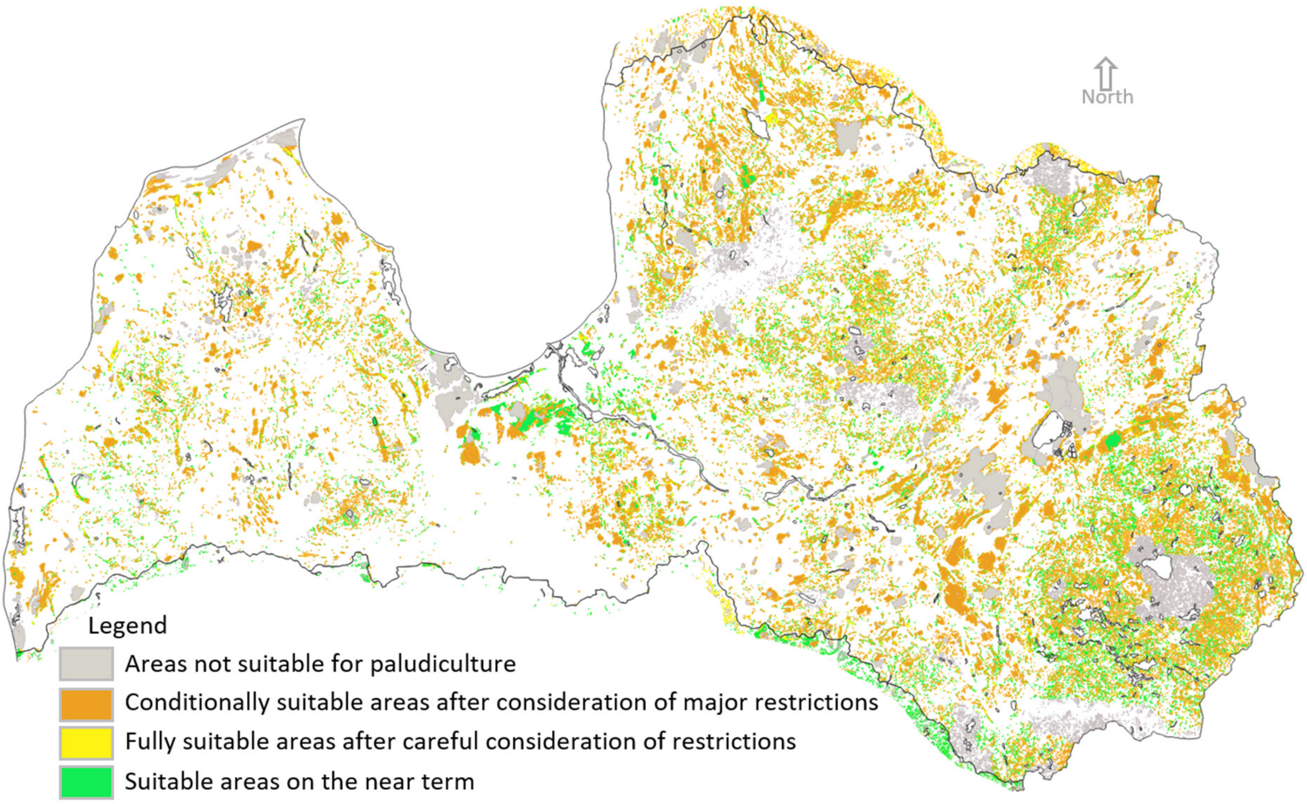

Figure 6. Potential for paludiculture [28].

In Latvia, legislative acts mandate the reclamation or restoration of all peat extraction sites. However, they do not detail the methods or principles for selecting a specific approach [30]. The most common post-extraction uses include afforestation, water body development, abandonment, and revitalization. Paludiculture, accompanied by rewetting, has not been widely accepted primarily due to the required mindset shift from melioration to rewetting, limited economic benefits (from a non-established market and products), and unsuccessful attempts at rewetting and paludiculture trials. Moreover, there is a lack of large-scale paludiculture examples to serve as encouragement for altering conventional management practices.

What is necessary to encourage the cultivation of paludiculture and the use of biomass in Latvia? To understand this, we must (1) assess technological and economic support opportunities for the development of paludiculture product valorization chains, e.g., investment, specialized equipment, market research for potential products, and farmer knowledge development. (2) Promote research and demonstration projects on good agricultural practices and set an example for the development of paludiculture in Latvia.

(3) Ensure coherence between climate change and agricultural policies by limiting the use of peat soils and supporting peatland rewetting and the cultivation of *paludi*-biomass by (1) extending the list of agricultural crops to include species suitable for growing on wet peat soil, such as reed, moss, cattail, etc.; (2) land users should be encouraged to grow paludiculture by including agri-environment and ecosystems related to the wet use of organic soils in the Common Agricultural Policy Strategy Plan; (3) updating organic soil inventory which is required for spatial planning and GHG emission reporting since the last soil mapping was carried out several decades ago; (4) agricultural areas should be subdivided into those containing mineral or organic soils and different support measures for each should identified.

Furthermore, implementation upscaling is crucial for paludiculture. On-site activities such as peatland rewetting, implementation of paludiculture (including infrastructure and facilities for biomass harvest), and off-site activities for the development of paludiculture products and product valorization chains (joint ventures between research, product engineering, and entrepreneurship) must be ensured. However, it is unclear who would be responsible for these steps as there is an overlaying interest and management by different ministries and organizations.

For centuries, peatlands and organic soils have been managed by draining them to use in forestry, agriculture, or peat extraction. However, there is an ongoing and lively debate about whether it is more beneficial to manage these soils in a drained state or to undergo rewetting [4,31]. Recently, a position paper was published stating that active afforestation of drained peatlands is not a viable option for climate mitigation and, therefore, to restore degraded peatlands, hydrological conditions must first be improved, primarily through rewetting [32]. The recent acceptance of the EU Nature Restoration Law added more turmoil to this debate, where the rewetting of 30% of the EU's drained peatlands by 2030 is now omitted, and economic and food security has been prioritized over nature restoration. Discussions both before and after the adoption of the new law highlighted the primary concerns regarding the rewetting of organic soils and, consequently, paludiculture implementation in Latvia:

- disruption of land use: rewetting efforts can conflict with existing land uses such as agriculture, forestry or peat production and impact livelihoods and local economies dependent on these activities;
- water management: rewetting can alter local water dynamics, affecting neighboring lands and can result in flooding of surrounding areas;
- infrastructure damage: rewetting can cause infrastructure, such as drainage systems, to deteriorate;
- methane emissions: while carbon dioxide emissions may decrease due to reduced decomposition, methane, a potent greenhouse gas, can be produced in waterlogged conditions. This can offset some of the carbon sequestration benefits.

Whilst there are differences in opinion regarding the rewetting and implementation of paludiculture, existing studies show the potential of paludiculture in terms of climate and biodiversity benefits [33]. For instance, full life cycle assessment studies suggest that paludiculture products could store carbon and substitute emission-intensive goods [34]. Furthermore, a thorough peer-review study analyzed the after-use of 356 peatlands [35] and found that extracted peatlands lack full socio-ecological, climate, and economic potential.

Regarding climate and biodiversity benefits, rewetting and paludiculture implementation managers should consider different aspects of success. For instance, the study of GHG from a re-vegetated cutaway peatland in Finland [36] indicated that five decades after peatland abandonment, it had a low or even negative annual carbon balance. Changes in vegetation species were the main reason for such an outcome. Nearly a decade after rewetting, the GHG balance in Irish cutaway peatland reduced notably (i.e., less warming) but was still higher than comparative intact sites [37]. Rewetted sites may be more sensitive to interannual changes in weather conditions, leading to a switch from an annual CO_2 sink to a source if triggered by drier site conditions. Rewetting following peat extraction in two Swedish peatlands [38] significantly promoted their colonization by plants and made a considerable contribution to the revegetation of these extracted peatlands. When water levels remained high and stable, *Sphagnum* growth provided appropriate conditions for native bog vegetation. Hence, the science-to-practice approach should be in the front line when one is considering rewetting and implementation of paludiculture. This is mainly due to the complex nature of peatland ecosystems, where knowledge of geology, hydrology, biology, and ecosystems is a basic need for the success of rewetting and paludiculture.

The importance of *Sphagnum* moss as a new raw material for growing media is described by Block [39], where he underlines that by the year 2050, the global population is projected to reach 10 billion. Along with this population growth, the demand for growing media is expected to more than triple, rising from 67 million m^3 in 2017 to 283 million m^3 in 2050. Specifically, the use of peat as a substrate, which amounted to 40 million m^3 in 2017, is estimated to double to 80 million m^3 in 2050. To meet the increased demand and the transition towards increased usage of wood, compost, and coir in substrates, it will be necessary to discover new substrate raw materials totaling at least 65 million m^3. Due to recent political decisions aimed at phasing out peat, there will be a requirement for 145 million m^3 of new raw materials. Presently, policymakers and researchers are primarily focused on addressing the challenge of replacing the currently extracted peat in amount of 40 million m^3 rather than initially confronting the projected 65 million m^3 increase in new raw materials, which are not yet available. Following this, they would address the projected 40 million m^3 increase in peat extraction, gradually reducing the volume of currently extracted peat. This strategic sequence of actions would allow consumers, growers, peat extractors, and scientists ample time for effective collaboration in developing new raw materials and adapting to their use.

Currently, peat extraction companies in Latvia are only establishing moss fields for experimental purposes or to grow donor material to reclaim other fields. At present, moss cultivation does not pay off for professional horticultural substrate growers. Furthermore, nearly all *Sphagnum* farming sites have obstacles and challenges ensuring the successful establishment and management of moss trial fields. For instance, the geological setting for most of the sites contains carbonate-rich glaciogenic sediment below a thin leftover (after extraction) peat layer. Under these circumstances, ensuring preferable growing conditions can be challenging as it is important to keep pH low (acidic) and omit nutrient enrichment through water supplies.

Applying the average cost per hectare of both *Sphagnum* sites—Rāķa Bog and Ķemeru Bog (LIFE Restore [40]), EUR 25,420 (Table 1), to all peat production areas in Latvia, which amount to 25,000 hectares, the installation of *Sphagnum* farming fields would cost nearly EUR 885 million (assuming that *Sphagnum* farming would be feasible and successful in all peat extraction fields). Additional expenses for planning, project management, adapted machinery, employee training, monitoring, and other factors should also be considered.

According to Gaudig et al. (2017) [41], a harvest of 19.5 tons per hectare of dry mass was achieved after 9 years in northwest Germany. Assuming similar results in Latvia, a preliminary estimate suggests that approximately 0.5 million tons of dry mass could be harvested from 25,000 hectares 9 years after establishment, with subsequent harvests every 3–5 years. For comparison, over the past five years, peat production in Latvia has averaged 1.2 million tons (with a relative humidity of 40%) annually. These calculations emphasize that transitioning from peat to *Sphagnum* cultivation will require significant financial investment and a considerable amount of time.

5. Conclusions

Although the term "paludiculture" might seem new in Latvia, the cultivation of reed canary grass and black alder on wet organic soils has been practiced for decades. Some Latvian landowners have been engaged in these cultivation practices for years, even if they might not have been familiar with the term "paludiculture" or the associated environmental and climatic benefits. To determine which of the described areas qualify as paludiculture sites, further research is essential, primarily involving the monitoring of water levels to ensure they consistently remain above −30 cm, even during exceptionally dry periods.

Current examples in Latvia underline that *Sphagnum* as paludiculture is promising yet facing multiple obstacles. Small production volumes and challenging growing conditions from site to site indicate that, at present, *Sphagnum* farming cannot provide enough raw material to substitute horticultural peat at necessary levels. More knowledge, time, and investments are required.

Wet meadows hold significant ecological and economic value in Latvia. With sustainable management, these habitats can support biodiversity, offer drought-resilient fodder sources, and even pave the way for profitable paludiculture ventures.

Latvia holds considerable potential for paludiculture implementation, given its suitable conditions and available land. Nevertheless, paludiculture and rewetting are perceived as potential threats to forestry, agriculture, and peat production in Latvia. However, a comprehensive understanding of the site conditions, site-specific planning, the balance between biodiversity benefits and financial investments, and careful consideration of both short-term and long-term consequences can lead to the integration of paludiculture principles into organic soil management practices.

Prioritizing areas for rewetting that have less significant impacts on agriculture or forestry and collaborating with local stakeholders to determine mutually beneficial solutions, such as incorporating rewetted areas into eco-friendly agricultural practices, can help in tackling the challenges related to disruptions to land use.

Performing comprehensive hydrological assessments and modelling together with careful planning of infrastructure adjustments before rewetting to comprehend potential impacts on water flow and minimizing the impact on neighbouring areas are crucial to address concerns related to water management, infrastructure damage, and methane emissions.

Paludiculture implementation has the potential to play a crucial role in achieving Green Deal objectives, promoting biodiversity, creating new raw materials, and increasing the accumulation of peat and stored carbon. Nevertheless, this endeavor necessitates investment in terms of time and financial resources, changing centuries-old practices and a shift in mindset.

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