

Review

Agriculture on wet peatlands: the sustainability potential of paludiculture

Ralph J.M. Temmink^{a,*}, Kristiina Lång^b, Renske J.E. Vroom^c, Jens Leifeld^d, Christian Fritz^e, Walther Zeug^f, Daniela Thrän^f, Clemens Kleinspehn^c, Greta Gaudig^c, Josephine Neubert^c, Jürgen Kreyling^c, Jennifer M. Rhymes^g, Chris D. Evans^g, Wiktor Kotowski^h, Anke Nordt^c, Franziska Tanneberger^c

^a Copernicus Institute of Sustainable Development, Utrecht University, Princetonlaan 8a, 3584 CB Utrecht, The Netherlands

^b Natural Resources Institute Finland (Luke), Tietotie 4, 31600 Jokioinen, Finland

^c Institute of Botany and Landscape Ecology, University of Greifswald, partner in the Greifswald Mire Centre, Soldmannstr. 15, 17487 Greifswald, Germany

^d Agroscope, Climate and Agriculture Group, Reckenholzstrasse 191, 8046 Zurich, Switzerland

^e Department of Ecology, Radboud Institute for Biological and Environmental Sciences, Radboud University, Heyendaalseweg 135, 6525, AJ, Nijmegen, The Netherlands

^f Department System assessment of Renewable Resource Use, Helmholtz-Center for Environmental Research (UFZ), Permoserstr. 15, 04318 Leipzig, Germany

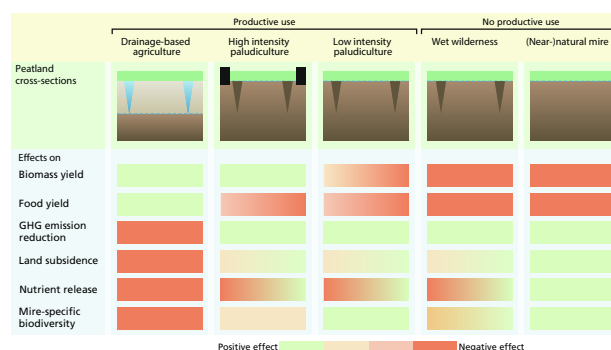
^g UK Centre for Ecology and Hydrology, Bangor, Deiniol Road, Bangor LL57 2UW, United Kingdom

^h University of Warsaw, Department of Ecology and Environmental Conservation, Institute of Environmental Biology, ul. Żwirki i Wigury 101, 02-089 Warszawa, Poland

HIGHLIGHTS

- Wet peatland use lessens economic and ecological trade-offs.
- Wet agriculture provides new business cases and can sustain livelihoods.
- Paludiculture aids in climate change mitigation and adaption.
- Rewetting halts biodiversity loss and prevents pollution.
- Paludiculture contributes to ten of the seventeen UN Sustainable Development Goals.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Humanity must overcome the polycrisis of biodiversity loss, climate change and pollution. These challenges are especially urgent in peatlands, which develop slowly under waterlogged conditions, function as landscape filters and store large amounts of carbon. Drainage for agriculture, forestry or peat extraction leads to severe socio-ecological impacts, including greenhouse gas emissions, biodiversity loss, land subsidence, higher flood and drought risks and downstream pollution.

OBJECTIVE: This study evaluates paludiculture as an innovative wet agricultural land use that maintains wet peatlands, offers economic alternatives to drainage-based systems and reduces environmental impacts.

METHODS: We reviewed and synthesized ecological and socio-economic evidence from low- and high intensity paludiculture practices to assess their potential to balance human needs with peatland conservation.

* Corresponding author.

E-mail address: r.j.m.temmink@uu.nl (R.J.M. Temmink).

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RESULTS AND CONCLUSIONS: Paludiculture is a promising new agricultural land use that effectively reduces greenhouse gas emissions, supports biodiversity restoration and contributes to climate mitigation and sustainable development. Our findings show direct and indirect contributions to ten UN Sustainable Development Goals: no poverty, good health, clean water, clean energy, innovation, sustainable cities and communities, responsible production, climate action, life below water, and life on land. Nonetheless, challenges remain regarding economic viability, land-use competition and management.

SIGNIFICANCE: Paludiculture shows how wetland agriculture can create new revenue opportunities combined with ecological protection. By contributing to both climate and biodiversity goals, it is a sustainable alternative to drainage-based peatland use.

1. Introduction

Humans are rapidly and often destructively transforming the Earth's lands and oceans (Foley et al., 2005). Consequently, humanity currently exists outside the safe operating space for at least six of the nine planetary boundaries: climate change, biosphere integrity, land system change, biogeochemical flows, freshwater change and novel entities (Richardson et al., 2023; Rockström et al., 2009; Steffen et al., 2015). The unprecedented rate of ecosystem degradation results in the loss of essential ecosystem functions, such as carbon (C) storage and sequestration, flood protection and water purification, with cascading effects on food insecurity, social inequality and environmental degradation (Diffenbaugh and Field, 2013; Leifeld and Menichetti, 2018). Humanity needs to implement targeted interventions to reduce the transgression of the planetary boundaries (van Vuuren et al., 2025). Specifically, to address the polycrisis of biodiversity loss, climate change and environmental pollution, the development and deployment of innovative, scalable and evidence-based solutions is urgently needed.

Peatlands are ecosystems in which environmental problems are particularly acute due to their slow formation and essential ecological functions, such as filtering water and storing carbon (Walton et al., 2020). Peatlands form over millennia under wet and anoxic conditions through the gradual accumulation of organic matter (Yu et al., 2010). Peatlands are the World's most organic carbon dense ecosystem with a global density of c. 1500 Mg C ha⁻¹, which largely surpasses forests on mineral soils with 200 Mg C ha⁻¹ in soils and biomass combined and mangroves with 900 Mg C ha⁻¹ (Temmink et al., 2022a). Wet conditions create habitats for highly specialized organisms, enable the removal and storage of carbon dioxide (CO₂) from the atmosphere and provide water purification by retaining nutrients (Parish et al., 2008; Rydin and Jeglum, 2013). Despite these valuable services, 12% of peatlands are drained and excavated at a large scale (Fluet-Chouinard et al., 2023; UNEP, 2022). Peatland drainage generates 4.5% of global human-induced greenhouse gas (GHG) emissions via peat oxidation, increases the risk and severity of fires (generating additional CO₂ emissions and air pollution), causes annual land subsidence of 5 to 40 mm (which can lead to land loss in coastal regions) and drives biodiversity loss, eutrophication and downstream pollution (Erkens et al., 2016; Evans et al., 2019; Günther et al., 2020; Hein et al., 2022b; Hutchinson, 1980; Page and Hooijer, 2016). This creates billions of dollars of societal costs through damaged infrastructure, loss of productive land, health issues due to air pollution from peat fires, water management challenges and increased flooding (Hein et al., 2022a; Uda et al., 2019; van den Born et al., 2016). Agriculture on drained peatland can be highly profitable, for example for horticulture in the UK, dairy in Germany and the Netherlands and palm oil in Southeast Asia, but due to these negative consequences it conflicts with many global targets for sustainable development (United Nations Sustainable Development Goals; SDGs), climate change mitigation (Paris Agreement) and halting biodiversity decline (Kunming-Montreal Global Biodiversity Framework).

To mitigate these detrimental ecological and societal effects of destructive peatland use, large-scale raising of water levels in peatlands is urgently needed (Evans et al., 2021; Günther et al., 2020). Full rewetting involves 'all deliberate actions that aim to bring the water

table of a drained peatland (i.e., the position relative to the surface) back to that of the original, peat-forming peatland' (Convention on Wetlands, 2021). A water table close to soil surface suppresses peat oxidation and slows or stops ongoing land subsidence (Allan et al., 2023; Günther et al., 2020). Rewetting may further result in new accumulation of organic material that can re-establish the carbon sink function (despite a potential short-term peak in methane (CH₄) emissions after rewetting), which results in large amounts of avoided emissions and can reinstate a long-term sink for greenhouse gases (Günther et al., 2020). The reinstatement of peat accumulation can lead to a long-term increase in land elevation, while peat formation also results in the sequestration of nutrients, heavy metals and other pollutants, thus preventing downstream pollution (Strack et al., 2008; Temmink et al., 2024). Main land use options after rewetting can be categorized in (1) wet wilderness and (2) agriculture on wet peatlands (paludiculture) (Tanneberger et al., 2021).

In the first case, formerly drained peatlands are left to natural succession as wet wilderness in which no (or limited) management takes place. However, people that rely on drained peatlands for income often lack alternatives, except for targeted payments tied to rewetting and ecosystem services like water management, habitat creation, water purification and carbon storage. Paludiculture, on the other hand, allows continued agricultural use after peat rewetting. Paludiculture involves cultivation and harvest of either spontaneously established vegetation or deliberately planted crops under wet conditions, in which the peat is preserved or even increased (Michaelis et al., 2020), land subsidence is stopped and greenhouse gas emissions are minimized or reversed (Wichtmann et al., 2016). Typical paludiculture crops in the Holarctic are reed canary grass, common reed, cattail or peat mosses (Abel and Kallweit, 2023). The term 'paludiculture' was coined in 1998 and is derived from the Latin 'palus', which means 'mire, swamp' (Joosten, 1998; Wichtmann and Joosten, 2007). However, paludiculture as a form of land use existed already for millennia. For instance, societies lived in and used reed marshes, such as the Sumarians in the Mesopotamian Marshes over 3000 years ago (de Klerk and Joosten, 2019) or present-day reed harvesting around the globe (Köbbing et al., 2013).

This paper asks how paludiculture in Europe, a continent characterized by a large proportion of drained peatlands, can contribute to achieving the UN SDGs while balancing ecological opportunities with socio-economic trade-offs (Fluet-Chouinard et al., 2023; UNEP, 2022). We review and develop a forward-looking synthesis by explicitly linking paludiculture research to sustainability goals. We focus on the temperate zone because this is where the vast majority of paludiculture initiatives to date are situated (for boreal or tropical countries see Pouliot et al., 2015; Budiman et al., 2020; Lupascu and Wijedasa, 2021; Ziegler et al., 2021). We summarize the opportunities, risks, challenges and trade-offs of paludiculture through four cross-cutting themes that integrate ecological, socio-economic and policy research: (i) societal costs and biomass production, (ii) greenhouse gas emissions, soil carbon and land subsidence, (iii) nutrients, water quantity and quality and (iv) biodiversity. We analyze paludiculture through the lens of two land use intensities, namely low intensity and high intensity paludiculture and describe future prospects.

- **Low intensity paludiculture:** The productive use of semi-natural, undrained or rewetted peatlands through extensive, low-impact practices such as grazing or harvesting of aboveground vascular plant vegetation (e.g., grasses, sedges, reeds) in existing or spontaneously regenerated plant communities following rewetting. This form of paludiculture, sometimes referred to as permanent grassland paludiculture (Tanneberger et al., 2020), typically involves no or minimal active management of water levels, nutrients or species composition.

This definition excludes the gathering of peat moss (*Sphagnum*) from wild populations in (near-)natural bogs (c.f. Gaudig et al., 2018), where sustainable regrowth is slow (often taking decades), and where biomass removal may compromise peat preservation (and formation) and increase greenhouse gas emissions. Practices involving peat moss gathering, particularly in poorly drained or only partially re-wetted systems, are ecologically and politically debated, and are not considered part of low intensity paludiculture.

- **High intensity paludiculture:** Active agricultural or silvicultural use of peatlands following rewetting based on native or non-native species that are deliberately established (i.e., cropping paludiculture, Tanneberger et al., 2021). This involves more intensive management of water, nutrient levels, weed species or other agricultural interventions compared to low intensity paludiculture.

We did not consider other practices than rewetting (e.g., partial rewetting) and paludiculture (e.g., slightly peat-decomposing land use) and used a cross over point from GHG sequestration to emission at 10 to 15 cm water table depth (Bockermann et al., 2025; Evans et al., 2021). Thus, the potential impacts of wetter farming (i.e., wetter than the baseline but still drained) via partial rewetting or subsurface irrigation within conventional drainage-based agricultural systems are not addressed. Our paper largely focuses on the cultivation of native wetland species rather than non-native species (e.g., silvergrass (*Miscanthus spp.*) in Europe) or conventional food crops that can be grown under wet conditions such as rice. Photovoltaics on peatland is another novel land use type that we do not consider (Fakharizadehshirazi and Rösch, 2024).

2. Ecological and socio-economic effects of paludiculture

2.1. Societal costs and biomass production

2.1.1. Effects of rewetting

The societal cost of agricultural production on drained peatlands is high, because drained peatlands only provide 1% of the consumed kilocalories, but are responsible for 30% of GHG emissions from croplands worldwide (Carlson et al., 2017). The carbon cost of products from drained peatlands can be higher than the value of the products (Mattila, 2024). Peatland drainage increases the life cycle emissions of food (Heusala et al., 2020; Lazzerini et al., 2016) and rewetting or the relocation of conventional production from peatlands to mineral soils have a high potential to move societies closer to the goal of sustainable consumption and production (Fig. 2). GHG mitigation measures on peatlands, especially rewetting, are cost-efficient compared to many other sectors. The price per ton of CO₂ mitigated can be as low as €10-60 with mitigation measures for agricultural peatlands (Niemi et al., 2024; Willenbockel, 2024), but is poorly incentivized (ECA, 2021).

Paludiculture enables maintaining formerly drained peatlands in production, but alters product types and volumes (Niemi et al., 2024). In most cases it involves a transition from food to non-food crops, although this is not inevitable. The effects of transitioning to paludiculture on the value creation depends on raw materials produced, end products, cultivation and valorization practices (Segers et al., 2024) and on whether the farmer can be paid for the ecosystem services like GHG

mitigation. This can occur by agri-environmental payments, specific governmental payment schemes or private funding like in the voluntary carbon markets (de Jong et al., 2021). Converting drained peatlands to paludiculture requires also changes in machinery and crop type. Most promising paludicrops in Europe are cattail (*Typha spp.*), reed (*Phragmites australis*), peat moss (*Sphagnum spp.*), reed canary grass (*Phalaris arundinacea*), sedges (*Carex spp.*) and alder (*Alnus glutinosa*, Fig. 1). The related costs and currently unknown revenues limit the willingness of farmers to adopt paludiculture (Hansson et al., 2023). Therefore, well-shaped incentives need to support paludiculture adoption at farm level (Wichmann and Nordt, 2024).

Paludiculture biomass can be used to produce heat and energy, food and fodder, or for building materials or growing media (Fig. 1) (Abel and Kallweit, 2023; Wichmann et al., 2016). As markets of biobased materials are estimated to increase (Asada et al., 2020), paludiculture could have a relevant role in decarbonizing industries by providing novel types of biomass. In Germany for example, if 4-15% of biogenic raw materials in paper, construction, furniture, chemicals, cat litter and bioenergy industries were replaced by materials from paludiculture, it would lead to cultivation of 1.3-5 Mt of dry biomass on 250-989 kha of rewetted peatland area. This is 25 to 100% of the drained, agriculturally used peatlands that need to be rewetted to achieve Germany's climate targets (Systain, 2023).

2.1.2. Low intensity paludiculture

To date, the majority of paludiculture sites in Europe are low intensity. Rewetting and/or management are driven by nature conservation objectives (Wichmann et al., 2016). Due to agricultural policies relying much on area-based payments, many drained peatlands are currently not in productive use in the EU (Kekkonen et al., 2019), but can still be large sources of GHGs if drainage is active (Keck et al., 2024). Such drained sites may also develop to low intensity paludiculture, because they often are shallowly drained and naturally become wetter due to degrading drainage systems. Low intensity paludiculture can produce for example raw material for biochar and biogas processing, bedding used in manure management of stables or low-quality fodder (mixed grasses). In low intensity paludiculture, the costs for site preparation are often relatively low. The costs of ditch blocking without soil transport or planting costs can remain below 1.000 € ha⁻¹ (Grand-Clement et al., 2015). The main income for landowners in such cases would be biomass supplemented with payments for ecosystem services, such as carbon storage and sequestration, water quality, water retention or biodiversity benefits. Activities on peatlands that are wet without previous draining (e.g., reed harvesting) also fall into the category of low intensity paludiculture (Ziegler et al., 2021). The area of reedbeds in Europe, including those on mineral soils, has been estimated to be >6 Mha (Köbbing et al., 2013) and their biomass production can have local economic importance (Wichmann, 2017; Wichmann et al., 2017). Currently, Western European countries rely on imports of up to 85% of the national consumption of thatching reed, importing from South and East of Europe and even China, thereby emphasizing a demand and a market well beyond local or regional scales (Wichmann and Köbbing, 2015).

2.1.3. High intensity paludiculture

Continuing productive use after rewetting may be an appealing option for many landowners, but currently it is challenging to maintain the income at the level of conventional agricultural production (de Jong et al., 2021). The initiation of high intensity paludiculture is more costly than low intensity paludiculture due to elaborate planning, establishment of new crops, site infrastructure for logistics, water management systems, machinery or harvest services and potential losses of crop subsidies. The establishment costs of paludiculture vary from 2.000 to 30.000 € ha⁻¹ for reed and cattail (Wichmann et al., 2022) and from 40.000 to 130.000 € ha⁻¹ for peat moss paludiculture (take note: the costs are based on relatively small experimental sites and may get lower

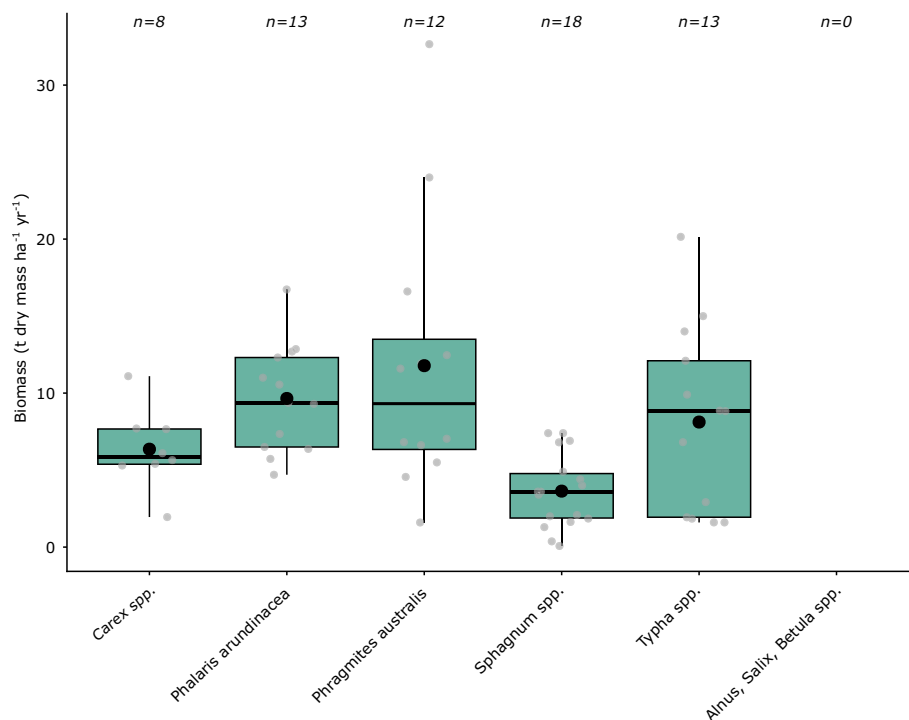


Fig. 1. Recorded yields of crops suitable for paludiculture. Biomass is in t dry mass ha⁻¹ year⁻¹. The data originate from organic soil with varying fertilizer application, harvest times and stand age. Trees like alder, willow or birch can be grown in paludiculture settings, but data on their yields on peat soils were not available. We did not distinguish between early and fully established paludiculture sites. Boxplots show the median (middle line) and mean (black circle), quartiles (boxes), 1.5 times the interquartile range (IQR) (whiskers), and the individual data values (gray dots). Dots outside the whiskers are extreme values. References for *Carex* spp.: 1-5, *Phalaris arundinacea*: 2-3, 6-11, *Phragmites australis*: 2; 4-6; 10; 12-14, *Sphagnum* spp.: 15-20, *Typha* spp.: 9-10; 14; 21-22. 1: (Corns, 1974), 2: (Steffenhagen et al., 2008), 3: (Schulz et al., 2011), 4: (Ławniczak-Malińska, 2023), 5: (Edwards et al., 2024), 6: (Vymazal and Kropfelova, 2005), 7: (Timmermann, 2009), 8: (Káplová et al., 2011), 9: (Hartung et al., 2023), 10: (Eickenscheidt et al., 2023), 11: (Nielsen et al., 2024), 12: (Granéli, 1989), 13: (Koppitz and Buddrus, 2004), 14: (Geurts and Fritz, 2018), 15: (Gaudig et al., 2014), 16: (Gaudig et al., 2017), 17: (Wichmann, 2021), 18: (Vroom et al., 2020), 19: (Grobe et al., 2021), 20: (Käärmelahti et al., 2024), 21: (Pfadenhauer and Wild, 2001), 22: (Titěra et al., 2023).

with wider implementation; Wichmann et al., 2017; Wichmann et al., 2020; Ozola et al., 2023). Biomass crops suitable for paludiculture typically yield 3 to 14 t of dry matter ha⁻¹ year⁻¹. The variability is high both between and within crop types (Figure 1). The site conditions affect the biomass productivity and quality (Ren et al., 2019), but part of the variability results from intentionally choosing practices like infrequent harvest when there is no need to maximize production (Nielsen et al., 2024).

As most paludiculture crops are non-food crops, there are trade-offs between food and non-food production (Muscat et al., 2020) and potential socio-economic implications on farm economy. However, a large part of farm income could originate from paludiculture in the future. Europe has c. 5.9 Mha of cropland and grassland on drained peatlands (van Giersbergen et al., 2025). The potential of biomass production in this area is 47 Mt dry matter (area × mean biomass yield of 7.9 t ha⁻¹, Fig. 1). The value of the alternative crops replacing conventional production would amount to ca. 3.700 M€ (with mean European price of 79 € t⁻¹ estimated for under-utilized crops in energy use) (Panoutsou and Alexopoulou, 2020). The biomass yield would be 10.5% of the annual wood use of 446 Mt in the EU (Knowledge Centre for Bioeconomy, 2025). This coarse estimate suggests that the economic value of paludiculture and its potential to strengthen the climate-change mitigation potential of the EU both by reducing GHG emissions at the rewetted sites and by substituting fossil resources with annual raw material from paludiculture to help decarbonize industries is significant. There is potential to produce wood in paludiculture from water-tolerant species like alder, willow or birch, but data on their yields on peat soils are limited (Fig. 1). Further work is needed to estimate the potential of each crop based on more realistic criteria on the production site properties (Geurts et al., 2020), harvest timing and rates (Dragoni et al., 2017; Hartung

et al., 2023; Pijlman et al., 2019) and prices in more value-creating applications than bioenergy (de Jong et al., 2021).

2.1.4. Future prospects

While paludiculture has high potential, a survey among paludiculture practitioners showed that missing value chains, missing economic incentives and agricultural policies were great obstacles for implementation (Ziegler et al., 2021). Well-planned societal transition is needed to overcome bottlenecks in rewetting and paludiculture value chains: the rewetting and cultivation practices are not well-known by landowners or supported by agricultural policies, logistics and lack of innovations restrict use of the raw materials in industries and consumers do not sufficiently recognize the sustainability issues related to drained peatlands. The key for a transition to sustainable peatland use and farm security lies in agricultural policies, proper payments for ecosystem services and the development of voluntary carbon credit markets (Chen et al., 2023), while also other factors such as training, narratives and availability of crops, harvesting and processing machinery should not be underestimated. The authorities responsible for land use planning could make rewetting services easily available for landowners and the new paludiculture crops eligible for similar agricultural subsidies as conventional crops. As wood harvesting is one of the reasons decreasing the carbon sink of European forests (Koroso et al., 2023), societies should recognize the potential to strengthen the carbon sink of the LULUCF sector with paludiculture, not only by GHG mitigation but also by replacing fossil material and wood with biomass (Hildebrandt et al., 2017).

Large-scale paludiculture is unlikely to develop before large industrial facilities utilize these crops, thus specific incentives are needed for industries to widen their raw material range. Innovations for machinery

or industrial processing of novel materials can be promoted with research and development funding (Ziegler, 2020). However, the overall sustainability in production and consumption also requires exnovation; the termination of previously innovative but nowadays outdated and unsustainable practices (Sommer and Frank, 2024). For peatlands this entails restrictions on new drainage and deepening of existing drainage and a future ban of subsidies for drained peatland use. Consumers should be informed about the carbon and biodiversity footprints of products from drained peatlands and the potential to improve sustainability with purchasing decisions for paludiculture products (Lahtinen et al., 2022). This knowledge can be improved by Life Cycle Assessment information on product level, considering the manifold environmental, economic and societal effects of the new production systems. When considering the many benefits and trade-offs for paludiculture-based products, holistic life cycle sustainability assessments have the potential to provide a coherent picture and support decision makers in policy and industry (see Box 1). To improve understanding of the possibilities to upscale paludiculture from the current small size or pilot scale to regionally significant business cases, best practice examples, more economic data of rewetting actions and wet peatland management and further biomass applications are urgently needed.

2.2. Greenhouse gas emissions, soil carbon and land subsidence

2.2.1. Effects of rewetting

Peatlands drained for agriculture, forestry and peat extraction emit greenhouse gases, often at exceptionally high rates (IPCC, 2013; UNEP, 2022) (Fig. 2). These emissions mostly comprise CO₂, but also large amounts of nitrous oxide (N₂O), both stemming from aerobic decomposition of peat and the concurrent microbial transformation and release of nitrogen (N), as well as from N fertilization (Günther et al., 2020; Wang et al., 2024). Specifically, CO₂ flux values are negative with c. -2 t C ha⁻¹ yr⁻¹ at a water table of 0 cm and increases to c. 8 t C ha⁻¹ yr⁻¹ at a water table of -80 cm for temperate and boreal peatlands (Evans et al., 2021). Furthermore, worldwide N₂O fluxes are highest from drained sites with 7.3 kg N₂O-N ha⁻¹ yr⁻¹ and almost 12- and 20-times lower in rewetted and natural sites with 0.63 and 0.35, respectively (Lin et al., 2022). In addition, emissions of CH₄ from drained peatlands can occur from local wet zones such as ditches (Clifford et al., 2025; Gan et al., 2024; Hendriks et al., 2024; Peacock et al., 2021) or during periods of high water levels (i.e., when aerobically initially decomposed organic matter becomes flooded and enters anaerobic microbial metabolic pathways). Globally for CH₄, near-natural peatlands emit 228 kg CH₄ ha⁻¹ yr⁻¹, while the drained portion of peatlands emit 19 and the ditches

that typically account for 4% of the area emit near 700 CH₄ ha⁻¹ yr⁻¹ (Gan et al., 2024).

Peatland rewetting is key to curbing emissions related to aerobic peat decomposition (Humpenöder et al., 2020) and needs to be part of global climate action. Aerobic peat decomposition is spatially tightly linked to the oxic zone of the peat deposit, so permanent raising of the water table strongly reduces both CO₂ and N₂O emissions, whereas CH₄ emissions increase once the water table is within ~20 cm of the surface due to increasingly anoxic (reducing) soil conditions (Couwenberg et al., 2011; Evans et al., 2021; IPCC, 2013; Kettridge et al., 2015). Although elevated CH₄ emissions partly impair the climate benefit of rewetting, natural peatlands are climate cooling in the long term due to their continuous net CO₂ uptake as accumulated peat and the short atmospheric lifetime of CH₄ (Frolking and Roulet, 2007; Günther et al., 2020). The continuous nature of the peat decomposition process and the long atmospheric lifetime of CO₂, also mean that the cumulative warming impacts of peatland drainage are extremely high (Günther et al., 2020). Hence, rewetting peatlands does not only reveal an immediate GHG benefit over peatland drainage but also allows to avoid further positive radiative forcing and may achieve a negative radiative forcing after decades to centuries (Leifeld et al., 2025; Ojanen and Minkkinen, 2020). The formation of peat in temperate fens occurs mainly via belowground biomass (roots), while in bogs it occurs mainly via moss biomass at the edge of the oxic and anoxic layer (Michaelis et al., 2020). Next to GHG mitigation, rewetting (and paludiculture) helps with climate change adaptation. For example, enhanced water storage in the landscape can offset increased drought risks connected to global warming (Karimi et al., 2024). Also, evapotranspiration from wetlands provides local cooling and creates an oasis effect via the lowering of evapotranspiration from surrounding production landscapes, which improves conditions for farming and forestry (Huryna et al., 2014; Kelvin et al., 2017; Suggitt et al., 2018; Wahren et al., 2016).

Rewetting for either wilderness or paludiculture can be expected to halt the major GHG emissions associated with peat oxidation. However, the overall GHG outcomes are unlikely to be identical, because paludiculture introduces new carbon fluxes not typically present in natural systems. These include carbon exports via biomass harvest, potential carbon and nutrient inputs and hydrological modifications to enable specific management goals, such as increased productivity or ease of harvest. Additionally, one should also account for the C-footprint of management practices and biomass transport and processing. Furthermore, the climate impact of paludiculture is significantly influenced by the fate of the harvested biomass. If the biomass is used for short-lived applications like forage, the carbon is rapidly returned to the

Box 1

Holistic and Integrated Life Cycle Sustainability Assessment (HILCSA)

The sustainability of land use systems like paludiculture can be evaluated using life cycle sustainability assessment (LCSA), which considers environmental, economic, and social impacts throughout a product or system's entire life cycle. Life cycle assessment is well introduced and standardized and can be built on open access data bases (Finnveden et al., 2009). In LCSA however, environmental, economic, and social dimensions are treated separately, and trade-offs and synergies between the dimensions are neglected. In the context of products that are generated from materials grown on wet or drained peatlands (i.e., paludiculture versus classical crops) these shortcomings become substantial, because effects of the management practices are substantial. These entail complex interaction between greenhouse gas emissions, biodiversity, land use changes and socio-economic impacts. One approach for a coherent live cycle sustainability assessment is the Holistic and Integrated Life Cycle Sustainability Assessment (HILCSA), which integrates environmental, economic and social dimensions within a unified framework and links it to 14 of the 17 SDGs. HILCSA is able to reveal synergies and trade-offs that single-issue LCSAs, for example those focused solely on greenhouse gases, may overlook (Zeug et al., 2023, 2022). In the context of paludiculture, HILCSA holds potential to capture the complexity of socio-ecological interactions, especially regarding greenhouse gas emissions, biodiversity, land use changes, and socio-economic impacts. However, applications of HILCSA in paludiculture remain limited. While several case studies have shown its general capabilities (Zeug et al., 2023, 2022), there is a gap in reliable primary data on key ecological processes in paludiculture, such as soil carbon losses across different peatland types and management. As such, collecting high-resolution, site-specific primary data, especially on carbon dynamics, hydrological processes, and socio-economic conditions is necessary to gain a comprehensive, evidence-based assessment of the sustainability potential of paludiculture, guiding both policy and practice.

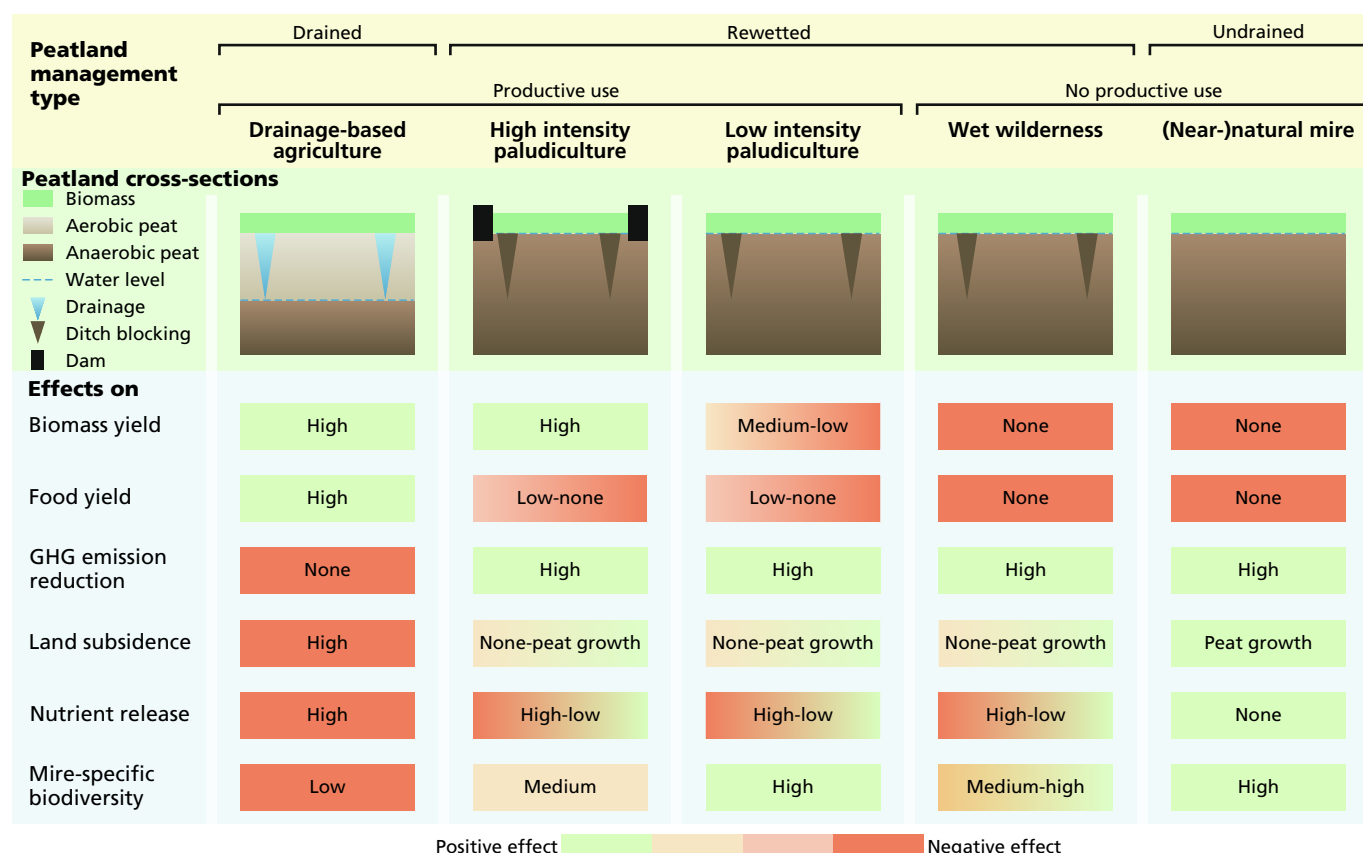


Fig. 2. Typical effects of peatland management types on biomass yield, food yield, GHG emission reduction, land subsidence, nutrient release and mire-specific biodiversity. The drained baseline assumes fertilization with associated high yields and nutrient losses, though yields may be lower on marginal drained peatlands. Nutrient release after rewetting depends on site history, plant uptake and soil chemistry, often reflecting past drainage or fertilization. Biomass and food yields are considered ‘none’ for wet wilderness or near-natural mires even though small harvests can take place; production would classify it as paludiculture. In some cases, biomass is cut for management but left on site or burned locally.

atmosphere, representing a true carbon loss. Conversely, utilization in long-lived products (e.g., construction materials) can delay or prevent emissions. These fluxes must be carefully accounted for to assess the true climate impact of paludiculture systems, for which there is currently limited data. For the purposes of the studies reported below, we treat harvested carbon as true losses unless otherwise stated.

2.2.2. Low intensity paludiculture

Low intensity paludiculture typically adopts a ‘use what grows’ approach, where vegetation re-establishes following rewetting with minimal management. Fertilizer inputs are absent, harvesting is often limited to annual biomass removal, or extensive grazing takes place. As such, GHG balances are closer to those of rewetted conservation peatlands with modest carbon exports that must be accounted for in carbon budgets. Studies on the effect of low intensity paludiculture on GHG emission are scarce. A two-year field study by Günther et al. (2014) evaluated the net ecosystem carbon balance (NECB) of a rewetted fen site (15 years post-rewetting), where different vegetation communities dominated by reed, broadleaf cattail (*Typha latifolia*) and lesser pond-sedge (*Carex acutiformis*) were subject to harvested and unharvested treatments. When expressed in CO₂-equivalents, harvesting generally increased net GHG emissions. For cattail, emissions rose from −1.21 to +9.44 t CO₂-eq ha^{−1} yr^{−1} in year one and from +3.56 to +12.37 t CO₂-eq ha^{−1} yr^{−1} in year two. Reed shifted from a sink (−2.64) to a source (+13.50) in year one, with smaller increases in year two (+2.53 to +3.09). Sedges showed the most variable response, with harvesting increasing emissions from +1.65 to +16.19 t CO₂-eq ha^{−1} yr^{−1} in year one, but reducing them from +3.08 to −0.81 in year two. Taken together, studies show that low intensity paludiculture can substantially reduce

GHG emissions compared to drained peatlands, where annual fluxes often exceed 20–30 t CO₂-eq ha^{−1} yr^{−1}, but may not achieve a net CO₂ sink where biomass off-takes are significant (Bockermann et al., 2025; Bockermann et al., 2024; Günther et al., 2014). In the absence of direct measurements of peat subsidence/formation for paludiculture sites, most studies assume that peat subsidence will be halted, based on well-established water table-peat subsidence relationships (e.g., Dawson et al., 2010; Evans et al., 2019; Ma et al., 2022; Van den Akker et al., 2007). In the first field-based study to quantify the balance of production and decomposition under different management and nutrient regimes in rewetted fens, paludiculture did not negatively affect the peat formation potential (Kreyling et al., 2025).

2.2.3. High intensity paludiculture

High intensity paludiculture systems are characterized by a wide range in harvest frequency from multiple harvests per year to every couple of years with substantial biomass exports and various potential interventions including land preparation, planting, weed or pest control and dynamic water table management, which all add a greater complexity to GHG accounting. We discuss some of these and their impacts on GHG emissions below.

To support mechanized harvesting and crop establishment, land preparation in high intensity systems may involve re-leveling, ditch construction or even topsoil removal (Gaudig et al., 2018; Käärmelahti et al., 2024; van den Berg et al., 2024). While these interventions can improve accessibility and nutrient conditions, they risk exposing peat from anaerobic layers to oxygen, temporarily increasing CO₂ emissions. In particular, van den Berg et al. (2024) report that topsoil removal can result in carbon losses as high as 557 t CO₂ ha^{−1} if the topsoil is not stored

under anoxic conditions over the period needed to decompose the organic matter, an impact that should be avoided if possible. Where nutrient removal is required to achieve biodiversity objectives, growing initial high-nutrient-demand paludiculture crops may offer a less destructive alternative to topsoil removal. The use of artificial fertilizers is often restricted on saturated soils (e.g., in Germany), but has still been reported in some studies. Kandel et al. (2019) observed short-term spikes in N_2O emissions following fertilization of reed canary grass with $160 \text{ kg N ha}^{-1} \text{ yr}^{-1}$. While background emissions remained low, cumulative N_2O emissions reached up to $6 \text{ kg N}_2\text{O-N ha}^{-1}$ in the first year and 4.2 kg in the second year, particularly following fertilizer application. Similarly, the use of nutrient-rich irrigation water has been linked to localized N_2O emission peaks (Kandel et al., 2019; van den Berg et al., 2024; Vroom et al., 2018). These findings underline the need for careful nutrient management, especially on nutrient-rich peat soils where additional inputs may not be necessary. On the other hand, some level of fertilization may be needed to achieve economically viable yields of some crops, ideally from nutrient-rich surface waters, but this warrants future research.

Dynamic water table control is occasionally used in high intensity paludiculture systems to facilitate access for machinery or support crop-specific growth phases (e.g., Gaudig et al., 2018). This is where the water table may be lowered for short periods of time to allow for a harvest, for example. Fluctuating water levels can increase aerobic conditions and risk pulse of CO_2 and N_2O emissions (Dinsmore et al., 2009; Günther et al., 2020). Despite these complexities, field studies show that high intensity paludiculture can still deliver considerable climate benefits compared to drained peatlands. For example, the review by Bianchi et al. (2021) reported average emissions of $18 \text{ t CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$ for paludiculture systems with emergent crops, compared to substantially higher emissions from drained agricultural peatlands. Peat moss cultivation was found to be a net GHG sink ($-2.8 \text{ t CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$), although this estimate did not account for carbon exported in the harvest. Given typical harvest rates of $3.2 \text{ t DM ha}^{-1} \text{ yr}^{-1}$ (Wichmann et al., 2020), the adjusted balance may approach closer to $\sim 6 \text{ t CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$, but this can substantially vary depending on how much of the crop is harvested. van den Berg et al. (2024) further examined net GHG balances for narrowleaf cattail, broadleaf cattail and water fern (*Azolla* spp.). Only narrowleaf cattail acted as a net GHG sink ($-1.4 \text{ t CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$), while broadleaf cattail and water fern were net sources (10.5 and $2.9 \text{ t CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$, respectively) due to high CH_4 emissions. Nonetheless, all paludiculture crops outperformed the adjacent drained reference site, which emitted $20.6 \text{ t CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$.

It should be noted that these findings are often based on small-scale experiments, with limited harvesting or operational constraints (Buzacott et al., 2024; van den Berg et al., 2024; Vroom et al., 2024). As such, real-world scaling may introduce additional variables not captured in these experiments. High intensity paludiculture introduces greater complexity in management and GHG accounting compared to low intensity. However, when well-managed, with appropriate water levels, minimal nitrogen inputs and thoughtful site preparation, these systems can offer substantial net climate benefits over conventional drained land use (Beetz et al., 2013; Beyer and Höper, 2015; Bianchi et al., 2021; Daun et al., 2023; Günther et al., 2017; Huth et al., 2022; van den Berg et al., 2024). Similar to low intensity paludiculture, data on peat subsidence or growth are absent.

2.2.4. Future prospects

The majority of studies reveal significant improvements in the GHG balance of rewetted peatland sites both for low and high intensity paludiculture, relative to drained agricultural use. However, in many cases the systems remain a net GHG source despite rewetting (Beyer and Höper, 2015; Bockermann et al., 2024; Daun et al., 2023). Whereas the database on CO_2 and CH_4 is already broad, measurements on N_2O and its drivers, as well as interactions between past-fertilization and fluxes of CO_2 and CH_4 , are less frequent. Importantly, few studies indicate that

even with biomass harvest, which is accounted for as CO_2 emission in commonly used approaches, a paludiculture system may become GHG neutral. In terms of reaching climate neutrality by 2050, such GHG neutral but managed systems are particularly interesting and identifying the factors and processes that result in GHG neutrality despite harvest removal is of utmost importance. In the long run, only paludiculture systems which are net carbon sinks (incl. its long-term products like building material) can contribute to climate cooling (Leifeld et al., 2025). GHG emissions from rewetted systems are characterized by a very high site-to-site variability, making it difficult to derive proper management recommendations. More studies comparing the effect of different paludiculture crops, or different management intensities of the same crop on the same site, would allow us to distinguish the effect of the crop and its management from that of the site and thereby develop more specific emission factors for the various types of wet management. Furthermore, data are lacking on the effect of paludiculture of various intensities on peat subsidence or formation.

2.3. Nutrient dynamics and water quantity and quality

2.3.1. Effects of rewetting

Peatland rewetting affects nutrient dynamics, water quantity and water quality (Fig. 2, Albert-Saiz et al., 2025; Rydin and Jeglum, 2013). The water quality determines whether a bog (rainwater fed) or fen-like (ground and rainwater fed) vegetation can be cultivated or established. Bog taxa, such as peat moss or sundew (*Drosera* spp.), typically thrive in water with a low pH (4–6) and low nutrient and bicarbonate concentrations ($<500 \mu\text{mol L}^{-1}$). In contrast, species like cattail, reed and willows are found in environments with higher pH levels (6–8) and relatively nutrient-rich conditions (Joosten et al., 2017; Rydin and Jeglum, 2013). Furthermore, rewetting affects biogeochemical cycles, particularly for nitrogen and phosphorus (P) (for C see GHG section). Specifically, it suppresses nitrification and promotes full denitrification, in which nitrate (NO_3^-) is converted to nitrogen gas (N_2 ; i.e., loss of N from the system). In parallel, existing ammonium (NH_4^+) is not converted to NO_3^- due to inhibited nitrification, which can lead to accumulation of ammonium in the porewater (Zak and Gelbrecht, 2007). Rewetting can cause the release of previously iron-bound P, which becomes bioavailable in the pore and/or surface water (van Diggelen et al., 2014; Zak et al., 2010; Zak and Gelbrecht, 2007). This can result in enhanced plant productivity, but also surface water eutrophication and downstream pollution (Venterink et al., 2002; Zak et al., 2018), if water is released to the receiving watercourse (i.e., outside dikes or polders). Moreover, rewetting of iron (Fe)-enriched systems may entail further nutrient (N, P) release and eutrophication due to the use of Fe^{3+} ions as electron acceptors by decomposing microbes (Emsens et al., 2016).

2.3.2. Low intensity paludiculture

Under low intensity paludiculture a peatland is rewetted as one-off action, such as ditch blocking or dam construction (Gaudig et al., 2018; Martens et al., 2023; Pouliot et al., 2015). The water table can be variable and may require management to protect the peat layer (Buzacott et al., 2024; Martens et al., 2023). Especially in strongly decomposed peat, the water table follows seasonal fluctuations and is subjected to stochastic events, such as drought or extreme precipitation. In addition, drainage of the surrounding (agricultural) lands extracts water from the rewetted area (Holden et al., 2004) and seasonality and landscape drainage can greatly affect the water level and the yield of paludicrops (Gaudig et al., 2020; Haldan et al., 2022).

Paludicrops under low intensity management depend on nutrients available *in-situ*, which are often supplemented by 'natural' sources (which might be elevated compared to pristine conditions as a result of drainage, fertilization and nearby agriculture), such as nutrients in ground, surface and/or rainwater and atmospheric deposition (mainly N). For example, innutrient deprived soils reed can achieve 3 times higher yields when grown under high N-addition ($300 \text{ kg N ha}^{-1} \text{ yr}^{-1}$)

compared to no addition ($0 \text{ kg N ha}^{-1} \text{ yr}^{-1}$) (Ren et al., 2019). Studies on former agricultural peatlands suggest a modest response of growth (1.5 to 2 times biomass increase) to nitrogen addition (Boonman et al., 2023; Vroom et al., 2022a). Biomass yield and quality (see production section) depend on the trophic state, nutrient limitations (e.g., nitrogen, phosphorus, potassium (K)) and nutrient stoichiometry (Bragazza et al., 2004; Gaudig et al., 2020; Haldan et al., 2022; Vroom et al., 2022b). Generally, P and K removal increases linearly with biomass yield for cattail and reed (Geurts et al., 2020). Through timed harvesting of cattail or reed in summer months, nutrients can be removed from the system with values of up to 600 kg N ha^{-1} , 80 kg P ha^{-1} and 450 kg K ha^{-1} (Geurts et al., 2020). By contrast, harvests in winter result in lowered nutrient export by up to 50 to 20% relative to maximum yields for October and February, respectively (Geurts et al., 2020). Nutrient limitation may become important in paludiculture sites that are harvested in summer, as winter harvest will allow for nutrient reallocation to belowground organs and may therefore stabilize nutrient pools in the long run (Geurts et al., 2020).

In addition, paludicrops effectively improve water quality through the sequestration of nutrients and through denitrification, may be used as buffer zone for N and P and can reduce downstream pollution (Geurts et al., 2020; Vroom et al., 2022b; Vroom et al., 2018). However, the effectiveness of peatlands as buffer zones is much higher for N than P (Walton et al., 2020) and additional measures may be needed to remove phosphates via precipitation to loamy material with river floods or via vegetation harvesting.

2.3.3. High intensity paludiculture

The initiation of high intensity paludiculture often includes a combination of topsoil removal, ditch blocking, dam construction, plant introduction and active water management with pump systems to regulate in and outputs (Gaudig et al., 2018; Lupascu and Wijedasa, 2021; van den Berg et al., 2024). This often results in more stable water levels that are adjusted to crop requirements compared to low intensity paludiculture (Brust et al., 2018; van den Berg et al., 2024). For example, at a peat moss paludiculture site in NW Germany, the water table is raised in accordance to the vertical growth of the peat moss lawn to achieve a water table of circa 5 cm below the top of the peat moss lawn (capitula) (Brust et al., 2018; Gaudig et al., 2024; Gaudig et al., 2020; Gaudig et al., 2014, 2018). In a landscape characterized by high N deposition ($20\text{--}40 \text{ kg N}^{-1} \text{ ha}^{-1}$), peat moss is able to thrive under optimal nutrient stoichiometry and stable high water levels (Gaudig et al., 2020; Temmink et al., 2017). Also, inadequate water quality may hamper establishment of target plants, like in The Netherlands for example, where bicarbonate-rich water has led to reduced growth or death of peat moss (Koks et al., 2025; Koks et al., 2024). Acidification of the surface water will remove bicarbonates, which facilitates peat moss's survival and growth (Koks et al., 2025; Koks et al., 2024). Crop selection should either be tailored to local site conditions or measures can be taken to create conditions suitable for the crop (e.g., artificial acidification, mowing, topsoil removal, see below). In addition, the water demand in paludiculture fields depends on the area, local water budget, season and year and generally more irrigation is required in dry years compared to wet ones (Brust et al., 2018; Temmink et al., 2024).

In high intensity paludiculture, topsoil can be removed to increase the hydraulic conductivity and/or remove excess nutrients or seeds of non-target plants. The depth of topsoil removal in paludiculture ranges from 10 to 60 cm. Recent research suggests that 5–10 cm of topsoil (sward) removal can be sufficient to prevent adverse effects of peatland rewetting, but this is site-specific (Daun et al., 2023; Käärmelahti et al., 2024; Quadra et al., 2023). Trade-offs of topsoil removal include possibility of that a certain nutrient can become limiting (for example potassium), high costs, land lowering, removal of large amount of carbon (severity depends on whether the removed topsoil will oxidize or not) and insect communities decline due to stoichiometric mismatches for multiple elements (Daun et al., 2023; Käärmelahti et al., 2023;

Klimkowska et al., 2010; Quadra et al., 2023; Vogels et al., 2024). Depending on nutrient status, active mowing of vascular plants can be required to create suitable light conditions for peat moss (Gaudig et al., 2018; Käärmelahti et al., 2023) and the exclusion of herbivores, such as geese, may be needed to enhance early establishment for cattail or reed (Geurts and Fritz, 2018; Temmink et al., 2022b). Nutrient addition experiments with cattail and reed show increased growth up to $50\text{--}150 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ without the nutrients becoming available in the surface water, indicating that these species can be used to purify the water (Haldan et al., 2022; Vroom et al., 2022b).

2.3.4. Future prospects

Recent research has shown that water quantity and nutrients play a key role in the productivity of paludiculture and the generation of ecosystem services. However, this research was often conducted in mesocosms or at small field sites. In general, questions remain open on whether and to what extent large-scale rewetting results in downstream pollution, mainly by phosphorus mobilization after rewetting highly decomposed peat (Zak et al., 2010), whether sufficient water is available at the landscape scale to facilitate full rewetting and how such a landscape-level rewetting would affect the local and regional water cycle. Rewetted peatlands could furthermore buffer high and low extremes in freshwater bodies by storing and releasing water. Furthermore, the need for fertilization to achieve sustained high yields and ways of fertilizing without causing surface water eutrophication and downstream pollution remain debatable. It has been suggested that high intensity paludiculture could transition into a biodiverse wilderness (Temmink et al., 2023), but such transitions after the removal of nutrients have not yet commenced and would have implications for the production of food and biomass. Scientist should create a clear frame which crops could and should be grown under which water quality, because the introduction of the wrong crop at a wrong place can lead to poor results (e.g., peat moss in location with high bicarbonate or cattail in nutrient-poor peat). Lastly, it remains to be studied how paludiculture practitioners should deal with trade-offs in water management, such as whether or not to irrigate with water of insufficient quality during a drought.

2.4. Biodiversity

2.4.1. Effects of rewetting

Permanent water saturation, peat formation, water storage and special microclimate make natural peatlands – mires – unique ecosystems and result in a very specific living environment (Albert-Saiz et al., 2025; Rydin and Jeglum, 2013). These ecosystems are home to specialized, mire-specific species (Fig. 2). Species that can also be found in other wet ecosystems, such as floodplains or wetlands without peat, are referred to as mire-typical species. At the species level, biodiversity is generally low in peatlands (harbouring on average 15% of local floras and faunas), but the prevailing species are highly specialised, which are generally not found in other habitats (Minayeva et al., 2017; Tanneberger and Wichtmann, 2011). By contrast, peatland biodiversity is high both at the genetic and ecosystem level, the latter expressed in distinctive surface patterns (Minayeva et al., 2017).

Even though paludiculture is wet agriculture and forestry, rewetting of drained peatlands has untargeted benefits for biodiversity, because wet habitats are rare in Europe. Monospecific paludiculture production fields, such as cattail, reed or peat moss, already support mire-typical and mire-specific species by providing essential habitats, enhancing ecological connectivity and serving as food sources (Luthardt and Zeitz, 2014; Närmann et al., 2021). Prolonged drainage has created novel ecosystems (Hobbs et al., 2009), disabling full restoration of the pre-degradation status, still many wetland species can re-establish in rewetted peatlands, including some now rare and often endangered species (Tanneberger et al., 2022). Rewetted peatlands can be similar to near-natural peatlands in terms of vegetation, microbiome, water level

and material balance, but can also differ significantly (Kreyling et al., 2021). A qualitative deviation in peatland functions from the near-natural initial state is likely and unsurprising due to its production function (Beckert and Rodríguez, 2023; Emsens et al., 2020).

Among the relatively few studies on the biodiversity of managed, wet peatlands, many have compared them with near-natural, unmanaged, wet controls. As paludiculture is to be established primarily on previously drained arable or high intensity grassland sites, these drained conditions should be used as a baseline for assessing the effects of paludiculture in general. Ideally, rewetted sites with different paludiculture intensities are included. Based on current knowledge, it can be assumed that paludiculture will lead to an increase in mire-typical and, under certain conditions, mire-specific biodiversity compared to drained areas (HNEE et al., 2024; Muster et al., 2015).

In addition to within-site effects of paludiculture, it is important to note the expected landscape-scale effects of increased ground water tables on re-establishing habitats of mire-specific and mire-typical species. Remnants of mire ecosystems, often protected in nature reserves, are typically adjacent to vast areas of drained peatlands, which deplete water from the landscape thereby hindering effective biodiversity conservation. With wise zonation, paludiculture can help to re-establish water storage in the landscape, restoring sufficient water pressure in adjacent protected peatlands (for the concept see Jurasinski et al., 2020; Temmink et al., 2023).

2.4.2. Low intensity paludiculture

Low intensity land use on rewetted peatlands may be the most beneficial to enhance biodiversity, but data is scarce. For example, rewetted fen areas dominated by sedges and cattail without cultivation and with different intensities of paludiculture were compared in NE Germany. This study, like others, found that mown sites have the capacity to host higher plant species richness than unmown sites. Quantitative analysis showed no consistent response of bird, carabid and spider response to the intensity of use of rewetted fen peatlands, regardless of dominant vegetation type (Martens et al., 2023). As the responses of the individual taxa varied, future management should aim to create a habitat mosaic with different management intensities (Martens et al., 2023). In fens mowing management can to some extent compensate for eutrophication, thus enlarging habitat range of light-demanding plant species (Kotowski et al., 2006) and mire-specific birds (Tanneberger et al., 2010).

2.4.3. High intensity paludiculture

In rewetted peatlands, vegetation in wet meadows and pastures often develops spontaneously. However, in actively cultivated paludiculture systems, plant species are often deliberately introduced (Tanneberger et al., 2020). In addition, other mire-typical and mire-specific species may also establish themselves, either by spreading from nearby natural areas or by arriving from the surrounding landscape. In high intensity paludiculture, management is needed to suppress unwanted dominant species (such as rushes, *Juncus spp.*), which can otherwise outcompete target species like peat moss (Gaudig et al., 2018). Interestingly, these management efforts can also create opportunities for the establishment of additional, from a conservation perspective, desirable mire-typical species.

In the largest peat moss paludiculture site in Europe in the bog Hankhauser Moor (17 ha), after up to 11 years of paludiculture use, a total of 16 moss species (incl. 7 peat moss species) and 68 vascular plant species were observed on the cultivated area and included bog-specific vascular plants like oblong-leaved sundew (*Drosera intermedia*), round-leaved sundew (*D. rotundifolia*), bog cranberry (*Vaccinium oxycoccos*) and white beak-sedge (*Rhynchospora alba*) (Gaudig et al., 2023). Fungi observed were typical species of natural peat moss lawns (Borg Dahl et al., 2020). In 2017–2022, 27 dragonfly species (33% of the species native to Germany) were recorded and in the 11 years since the area was established, 80 spider species were found with many red list species.

There was no sustainable change in the vegetation, dragonflies and spider communities with mosaic harvesting. This demonstrates the high biodiversity potential of peat moss paludiculture (Gaudig et al., 2023; Gaudig and Krebs, 2016).

For high intensity paludiculture on fens in NE Germany, it could be shown that such a site with great management intensity (cattail cultivation, 10 ha) had both the lowest and the highest qualitative biodiversity values, depending on the taxon. Despite its recent rewetting and isolated location, the high intensity cattail site hosts Red List species from all studied taxa (Martens et al., 2023). Specifically, the site became a hotspot for dragonflies, with 38% of the state's breeding dragonfly fauna recorded and 23% of this fauna probably reproducing (HNEE et al., 2024). In a 5 ha site with cattail, sedges and reed canary grass established in 2018 in S Germany, 18 breeding bird species were recorded, 6 of them on the regional Red List (Eickenscheidt et al., 2023).

2.4.4. Future prospects

All of the paludiculture sites studied so far are home to species of high national and international conservation value, which shows that not only protected 'wilderness' sites, but also wet agricultural sites of varying intensity can provide habitats for endangered species (HNEE et al., 2024; Muster et al., 2015). Efforts to understand biodiversity effects of paludiculture should be increased, especially those comparing management intensities on rewetted sites. We call for detailed studies across different species groups and fair comparisons against appropriate baselines. Moreover, sites with low productivity may still support high biodiversity, and in such cases, biodiversity gains could offset reduced production if these differences are recognized and monetarily compensated. For highly threatened mire-specific species reintroduction efforts may be needed and have proven to be successful (Morkvénas et al., 2025). Wet agricultural use of peatlands provides untargeted benefits that align with biodiversity restoration and conservation goals. Most promising are catchment-scale rewetting efforts that most likely enhance the management of paludiculture sites and benefits biodiversity (Ramchunder et al., 2012), which can be combined with site-specific management prescriptions. When properly embedded in paludiculture business models, biodiversity-promoting measures in paludiculture can be pursued. Possible measures within agricultural funding programs include, for example, prescriptions for ditch maintenance promoting biodiversity, one-year rotational fallows in wet meadows and bird breeding time adapted harvesting dates and intensity (Tanneberger et al., 2022). If we want the ecosystem services of wet peatlands and paludiculture to benefit society, we need to compensate them generously and clearly beyond a reimbursement of costs. Farmers must see their own advantage in providing ecological services (Hampicke, 2018).

3. Paludiculture contributes to ten SDGs

3.1. The contribution of paludiculture

The benefits of peatland rewetting and productive use lead to many interlinked positive effects and paludiculture could contribute directly and indirectly to ten out of seventeen SDGs (Fig. 3). Paludiculture provides income, clean water and responsible production for rural livelihoods and communities (SDG1 and SDG12). Current land-users maintain their income by paludiculture biomass business and nature-based payments for societal services, if available. Poverty can be reduced via lowered disaster risks (SDG1 in combination with SDG11). Specifically, wet peatlands in river floodplains reduce flood risk and lower water peaks for rural and urban areas and communities (SDG11). In addition, the reduction of fires and resulting harmful emissions in combination with clean water due to the peatland's water purification function benefits the health of humans (SDG3). Paludiculture also increases the variety and supply of sustainable bio-based raw materials for industry such as building material or growing media (SDG9) and the biomass can also be used to produce clean energy or heat (SDG7). The

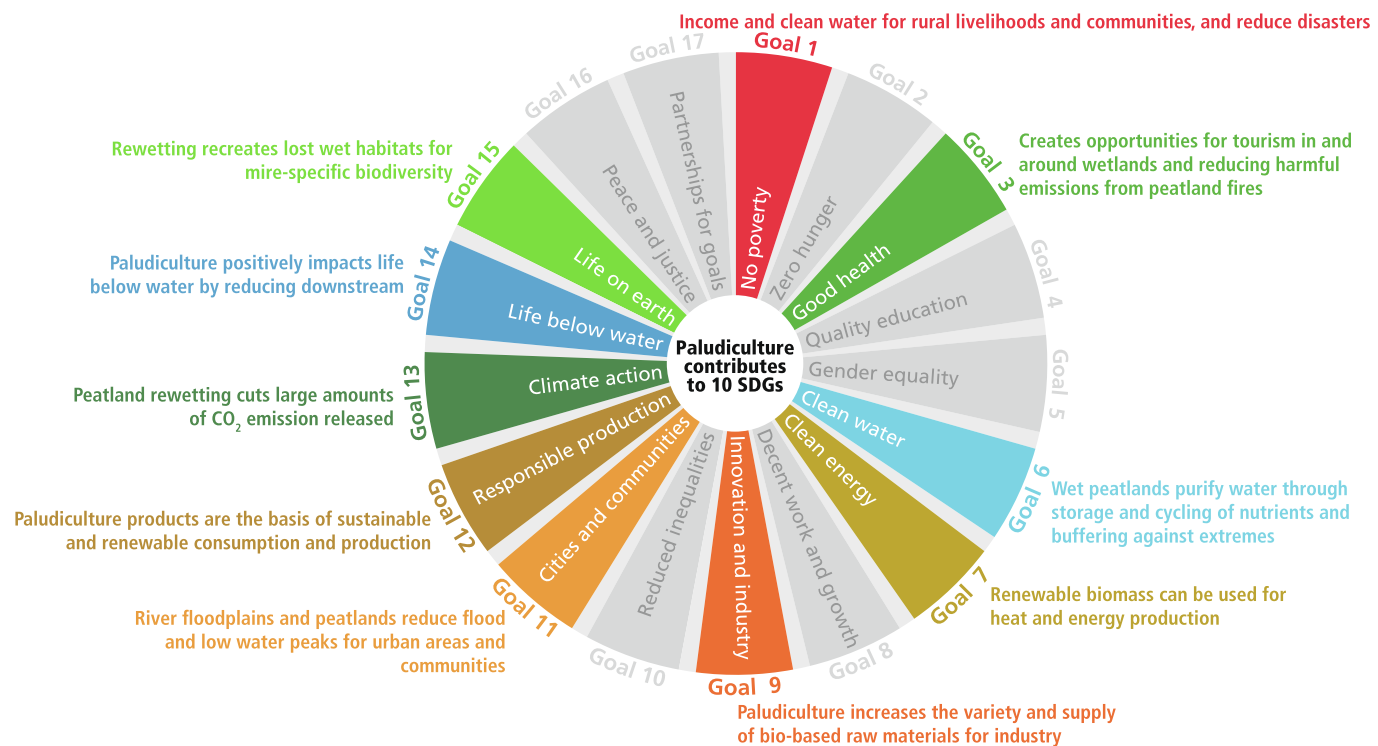


Fig. 3. The contribution of paludiculture to ten SDGs. Paludiculture contributes to ten SDGs, which are highlighted in color, while SDGs not influenced are shown in gray. Descriptions are based on [Tanneberger et al. \(2021\)](#). Wet peatlands without harvesting also contribute to many SDGs, such as SDG1, 3, 6, 11, 13, 14 and 15.

rewetting of peatlands cuts large amounts of CO₂ released and needs to be part of global climate actions (SDG13). Investments and subsidies to establish carbon neutral wet peatland use from public-private partnerships can strengthen business cases and local income (SDG1). Rewetting recreates lost wet habitats for mire-specific biodiversity (SDG15). These biodiverse wet landscapes create opportunities for tourism in and around the wetland (SDG3). Indirect effects of paludiculture include the reduction of downstream pollution, which reduces eutrophication and harmful algae blooms and benefits life below water (SDG14).

3.2. Prospects and challenges of paludiculture

Drained peatlands in temperate climates are agriculturally productive systems on which farmers produce a wide variety of food (e.g., vegetables, potatoes, corn), bioenergy and grass for dairy and meat ([van Giersbergen et al., 2025](#)). Regionally, promoting paludiculture may strengthen fiber and energy production and thereby income, allowing for increased food production on mineral soils using improved technology. As paludicrops are predominantly non-edible, a transition towards paludiculture may result locally or regionally in a net loss of food production or a net shift of bio-energy crops ([Carlson et al., 2017](#)). Indirectly however, paludicrops like peat moss can be used as raw material for sustainable growing media for tomatoes, cucumbers and peppers and can contribute to food production in controlled environmental agriculture (i.e., the practice of growing crops indoors where light, temperature, humidity and nutrients are carefully controlled to boost yield and efficiency, such as greenhouses or vertical farms ([McKeon-Bennett and Hodkinson, 2021](#))). Small-holder communities are not likely to switch to non-food paludiculture given their vulnerable position in food markets. Currently, national food security is becoming increasingly important due to changing global power structures and the loss of food production capacity is being criticized (e.g., [Moreno-Pérez et al., 2024](#)). A way forward towards just food security would be moving biomass production for bioenergy or animal fodder from high grade mineral to wet peat soils and production in paludiculture to more

efficiently use mineral soils for food production.

Paludiculture faces several practical and agronomic challenges that can limit its establishment and productivity. Weed pressure is often high in organic and nutrient rich soil, particularly during crop establishment (e.g., [Käärmelahti et al., 2024](#)). This can necessitate mechanical weed control, weed-sensitive water management and soil preparation, especially where clean, mono-crop harvests are required. The use of herbicides or insecticides remains controversial, raising environmental dilemmas and demanding regulatory choices. Establishing suitable crops is also complicated by climatic variability; while these systems are designed to remain wet, they remain vulnerable to weather extremes, such as flash floods and droughts, which can potentially cause crop failure. These risks are exacerbated when paludiculture is implemented at small spatial scales and surrounded by conventionally drained land, where hydrological isolation makes water level control more difficult and expensive ([Wichmann et al., 2020](#)). However, such challenges are expected to be mitigated when paludiculture is adopted at landscape scales, where coordinated water management and hydrological buffering become more feasible. It is also important to note the costs associated with land-use changes. Accessing wet fields typically requires specialized low-ground-pressure equipment ([Gaudig et al., 2018](#); [Wichmann et al., 2020](#)). These challenges highlight the need for context-specific management strategies, alongside continued innovation, supportive policy and targeted public investment to ensure the viability of paludiculture as a sustainable land use option ([Taylor and Stockdale, 2025](#)). Lastly, paludiculture is generally not well supported by the Common Agricultural Policy of the EU due to the restrictions in crop eligibility, but currently six member states enable eligibility of the most common paludiculture crops and thus maintaining the subsidies for the farmer ([Nordbeck et al., 2025](#)).

4. Conclusions

The last decades, evidence for paludiculture as a sustainable form of wet agriculture and forestry on peatlands has grown around the globe

(this paper and for a detailed report on paludiculture see [Taylor and Stockdale, 2025](#)). Our synthesis shows that paludiculture can contribute to solve the polycrisis of climate change, biodiversity decline and environmental pollution, while contributing to economic development of human societies ([Fig. 2](#)). Specifically, paludiculture contributes to ten of the seventeen UN's Sustainable Development Goals and can thus aid humanity to exist within the safe operating space of our planetary boundaries ([Fig. 3](#)). Overall, humanity should implement sustainable peatland management practices at large spatial scale ([Jurasinski et al., 2020; Temmink et al., 2023](#)). However, care should be taken for risks and challenges. The following ten take home messages should spur paludiculture research and benefit its large-scale implementation and societal acceptance:

- 1. Lessen ecological and economic trade-offs.** Paludiculture has the potential to solve the trade-off between economic development and rewetting through economic use of wet peatlands. Paludiculture transition should target heavily degraded areas first with for example fast land subsidence, rapid peat loss with infertile soils beneath (e.g., gravel, sulfur-rich, saline), fertility loss following erosion of the hydrophobic top layer, large fire and smog hazards.
- 2. Halt biodiversity loss.** Paludiculture can aid in the creation of rare wet habitats or corridors that support characteristic mire species through rewetting and vegetation management, both within and around the site (landscape-scale effects).
- 3. Mitigate and adapt to climate change.** Paludiculture is a viable solution to mitigate climate change by lowering GHG emissions and possibly through sequestration, which is needed to contribute to climate cooling beyond emission reduction. Paludiculture can contribute to climate change adaptation via water storage and lower drought risks in the landscape and through cooling via increased evapotranspiration (i.e., oasis effect).
- 4. Prevent environmental pollution.** Wet peatland use can prevent downstream pollution through altered biogeochemistry and phytoremediation and through sequestration and storage of nutrients in the plants and peat.
- 5. Land-use intensity flexibility.** The concept of paludiculture is flexible and can be tailored to the local socio-economic and landscape-ecological context, with a variety of options from low intensity to high intensity paludiculture.
- 6. Economic transition.** The concept of paludiculture is promising, but due to current policies, often not economically viable. Paludiculture thus requires subsidies or accompanying policy measures (e.g., carbon border adjustment mechanism for land-use products and climate action levelling mechanism to address the uneven distribution of climate change impacts and responsibilities between high emission land use and low emission land use countries). Large-scale implementation requires demand from the market for paludiculture products and economic incentives can aid to spur the transition and requires cessation (exnovation) of certain technologies, practices and rules.
- 7. Longevity of projects.** The long-term effect of rewetting and paludiculture management on yields, economic benefits, biodiversity, GHG balance, land subsidence and nutrients need to be assessed and be compared both to drained states and wet wilderness. For this, long-term funding (minimum 10 years) is needed.
- 8. Life Cycle Sustainability Assessment.** Assessments of products and services from paludiculture should consider the effects on the sustainability goals (SDGs) and can improve decision making in policy, industry and final consumers. Much improvement of data in publicly available databases for LCA is needed.
- 9. Further developed with and by rural communities.** Currently, paludiculture is almost entirely being developed and trialed by people who are not farmers (e.g., scientists, ecologists,

hydrologists, biologists). Large-scale adaptation of paludiculture needs to be co-created with rural communities and farmers. The establishment of value-chains with substantial co-benefits for and being centered within rural communities are the basis for a just transition ([Banerjee and Schuitema, 2023](#)).

- 10. Transformation of narratives.** The large-scale implementation of paludiculture requires support from societies. However, wet peatland narratives are often negative and thus need to be transformed. We should focus on solution-based narratives ([DeFries et al., 2012](#)), in which highlighting positive examples (i. e., 'bright spots') can provide a positive and solution-oriented role in education and capacity building.

CRediT authorship contribution statement

Ralph J.M. Temmink: Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Kristiina Lång:** Writing – review & editing, Writing – original draft. **Renske J.E. Vroom:** Writing – review & editing, Writing – original draft. **Jens Leifeld:** Writing – review & editing, Writing – original draft. **Christian Fritz:** Writing – review & editing, Writing – original draft. **Walther Zeug:** Writing – review & editing, Writing – original draft. **Daniela Thrän:** Writing – review & editing, Writing – original draft. **Clemens Kleinspehn:** Writing – review & editing, Writing – original draft. **Greta Gaudig:** Writing – review & editing, Writing – original draft. **Josephine Neubert:** Writing – review & editing, Writing – original draft. **Jürgen Kreyling:** Writing – review & editing, Writing – original draft. **Jennifer M. Rhymes:** Writing – review & editing, Writing – original draft. **Chris D. Evans:** Writing – review & editing, Writing – original draft. **Wiktor Kotowski:** Writing – review & editing, Writing – original draft. **Anke Nordt:** Writing – review & editing, Writing – original draft. **Franziska Tanneberger:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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