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ORIGINAL ARTICLE

Saving soil carbon, greenhouse gas emissions, biodiversity and the economy: paludiculture as sustainable land use option in German fen peatlands

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Abstract

Peatlands in the European Union are largely drained for agriculture and emit 25% of the total agricultural greenhouse gas emissions. Drainage-based peatland use has also negative impacts on water quality, drinking water provision and biodiversity. Consequently, key EU environmental policy objectives include the rewetting of all drained peatlands as an essential nature-based solution. Rewetting of peatlands can be combined with site-adapted land use, so-called paludiculture. Paludiculture produces biomass from wet and rewetted peatlands under conditions that maintain the peat body, facilitate peat accumulation and can provide many of the ecosystem services associated with natural, undrained peatlands. The biomass can be used for a wide range of traditional and innovative food, feed, fibre and fuel products. Based on examples in Germany, we have analysed emerging paludiculture options for temperate Europe with respect to greenhouse gas fluxes, biodiversity and indicative business economics. Best estimates of site emission factors vary between 0 and 8 t CO_2eq ha^{-1} y^{-1}. Suitability maps for four peatland-rich federal states (76% of total German peatland area) indicate that most of the drained, agriculturally used peatland area could be used for paludiculture, about one-third of the fen area for any paludiculture type. Fen-specific biodiversity benefits from rewetting and paludiculture, if compared to the drained state. Under favourable conditions, paludiculture can be economically viable, but costs and revenues vary considerably. Key recommendations for large-scale implementation are providing planning security by paludiculture spatial planning, establishing best practice sites and strengthening research into crops, water tables and management options.

Keywords Agriculture · Biodiversity · Ecosystem services · Greenhouse gases · Mitigation · Organic soil

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Introduction

Peatlands are a key terrestrial ecosystem to address multiple environmental issues. Sound peatland management practices can achieve greenhouse gas (GHG) emission reductions, climate change adaptation, water security and, at the same time, soil organic carbon (SOC) sequestration (Joosten et al. 2012; Bonn et al. 2016; Rumpel et al. 2020). Peatlands are lands with a naturally accumulated layer of peat at the surface (Joosten and Clarke 2002; Rydin and Jeglum 2013, Joosten et al. 2017). Peat is dead plant material with a high content of fixed carbon that has accumulated sedentarily under water-saturated conditions that induce incomplete decomposition. The presence or absence of vegetation and whether peat is currently being formed are irrelevant in this widely accepted broad definition of peatlands. Peatlands occur from tropical to arctic regions, cover c. 3% of the global land area (Parish et al. 2008; Joosten 2009) and contain c. 500 Gt carbon (Gorham 1991; Yu et al. 2010; Joosten et al. 2016a). This is equivalent to c. 20% of all global soil carbon and substantially more than the carbon stock in the global forest biomass (Joosten et al. 2016a). Peatlands can be either a carbon sink or—especially if drained—a carbon source (Couwenberg et al. 2011; Joosten et al. 2016a).

Globally, c. 10% of all peatlands are drained (Joosten 2009). A drainage 'hotspot' is the European Union (EU) where more than 50% of the peatland area is in a drained state (Tanneberger et al. 2017, 2021a). Drainage allows oxygen to enter the peat which enhances decomposition and results in the release of CO_2 from the fossil carbon store (Rydin and Jeglum 2013; Joosten et al. 2016a). Drained, degraded peatlands globally emit c. 2 Gt CO_2 equivalents (eq) per year (y^{-1}) (Joosten 2009; Leifeld and Menichetti 2018); those in the EU c. 220 Mt CO_2eq y^{-1} (Greifswald Mire Centre et al. 2020). This is both globally and EU-wide c. 5% of total GHG emissions. At the heart of peatland degradation is the unsustainable exploitation of land to maximise agricultural and forestry production. In the case of agriculture, 25% of total GHG emissions are from drained peatlands that only make up 3% of the agricultural land in the EU (Greifswald Mire Centre et al. 2020). Agriculture and forestry policies may be the game changers for a sustainable peatland management when harnessed to climate and biodiversity objectives.

Rewetting can substantially lower GHG emissions. In temperate Europe, rewetting grassland on drained peat soils saves up to c. 20 t CO_2eq ha^{-1} y^{-1}, and rewetting croplands even up to c. 30 t CO_2eq ha^{-1} y^{-1} (cf. Hiraishi et al. 2014; Wilson et al. 2016). The global mitigation potential from peatland rewetting (up to 2 Gt CO_2eq y^{-1}) is of similar size as that from SOC sequestration on all other agricultural lands (Leifeld and Menichetti 2018). In other words, comprehensive mineral soil abatement measures alone would only be able to compensate for the emissions from degrading peatlands instead of providing a net soil sink. Moreover, peatland restoration is, compared with mineral soil C sequestration, cheap in terms of nitrogen (N) demand, involves a much smaller land area and is thus more cost-effective (Leifeld and Menichetti 2018). Postponing rewetting increases the long-term warming effect of continued CO_2 emissions (Günther et al. 2020). Rewetting may also restore other ecosystem services of near-natural, undrained peatlands (Bonn et al. 2016). Depending on the water table, vegetation composition and various other factors, peat can even start to regrow, leading not only to a reduction of emissions, but to a net uptake of CO_2 (Wilson et al. 2016; Mrotzek et al. 2020). Peatland rewetting enables microbial recovery as a key prerequisite for new peat formation (Emsens et al. 2020). Until now, most peatlands have been rewetted for nature conservation purposes and productive land use was abandoned after rewetting. To respond to the globally increasing competition for land, to support rural livelihoods and to retain and restore wet grasslands as hotspots for biodiversity, in many cases, a simple cessation of land use is not an option. The solution is a fundamental transition to 'wet' agriculture or forestry, so-called paludiculture (Joosten et al. 2016b; Tanneberger et al. 2020a).

Paludiculture is productive land use of wet peatlands that stops subsidence and minimises emissions. Paludiculture comprises any biomass use from wet and rewetted peatlands, from harvesting spontaneous vegetation on near-natural sites to artificially established crops on rewetted sites (Wichtmann et al. 2016). Paludiculture produces biomass from peatlands under conditions that maintain the peat body, facilitate peat accumulation and can provide many of the ecosystem services associated with natural, undrained peatlands. It is a form of *carbon farming* with biomass use on organic soils (Tanneberger et al. 2020a). In the temperate zone, the subtropics and tropics, peat is often formed by roots and rhizomes and the above-ground biomass of such peatlands can (partially) be harvested without substantially harming peat formation and conservation (Joosten et al. 2016b). Besides traditional yields of food and fodder, the biomass can be used as fibre for construction materials, as fuel—also in form of high-quality liquid or gaseous biofuels—as well as raw material for industrial biochemistry, and for further purposes like extracting and synthesising pharmaceuticals and cosmetics (Wichtmann et al. 2016; Geurts et al. 2019). A comprehensive list of plant species that can be cultivated at peat-preserving water levels on peatlands can be found in the Database of Potential Paludiculture Plants (DPPP) (Abel et al. 2013).

The questions associated with the implementation of paludiculture require the cooperation of many scientific and technical disciplines in close feedback with practice. New crops that can thrive under permanently wet conditions have to be developed for, or adapted to, new production concepts. Furthermore, the complex interactions and effects of management under wet and drained conditions have to be studied, and the positive and negative effects on various ecosystem services associated with land use have to be evaluated (Schröder et al. 2016). Pilot projects are essential to further develop management and harvesting techniques, obtain robust data on environmental effects and create markets for products (Geurts et al. 2019). The urgently required research on paludiculture needs to not only capture the novelty of paludiculture use, but also that of the rewetted land, which may have long-lasting differences to pre-drainage conditions (Kreyling et al. 2021).

In this paper, we focus on paludiculture on fens, which are peatlands that receive ground- or surface water and that are widespread in temperate Europe (Joosten et al. 2017). Details on paludiculture types on fens addressed in this study can be found in Online Resource 1. To better understand the GHG mitigation potential, we derive tentative GHG emission factors for key fen paludiculture options in Germany, collated from literature and based on existing IPCC datasets (Drösler et al. 2014; Blain et al. 2014). To analyse the area potential, we modified and transferred an existing paludiculture land classification (Tanneberger et al. 2020b) to three additional federal states of Germany (based on administrative restrictions). Hence, we present a tentative assessment for potential fen paludiculture areas in four peatland-rich German federal states (representing 76% of the total German peatland area). For one of the three newly mapped federal states, we demonstrate the potential reduction of GHG emissions from implementing paludiculture. Furthermore, we summarise knowledge on biodiversity impacts and the economic competitiveness for the studied fen paludiculture types based on literature reviews. The results may be also applied in other temperate fens in Europe. We discuss gaps and opportunities and give an outlook on the large-scale implementation of paludiculture in Europe.

Methods

To comprehensively investigate the characteristics of the studied paludiculture types, we combine careful compilation and analysis of literature data and unpublished data with spatial analysis of paludiculture suitability classes and GHG mitigation potential.

Delineation of soil types and drainage condition

There are no definitions of 'peat' and 'peatland' by the Intergovernmental Panel on Climate Change (IPCC; Hiraishi et al. 2014), and both IPCC and United Nations Framework Convention on Climate Change (UNFCCC) national GHG inventories refer to 'organic soils'. We follow the approach taken in the National Inventory Submission of Germany (UBA 2020) and include all soils meeting the UNFCCC criteria for 'organic soils', i.e. not only histosols but also peaty soils.

To characterise drainage conditions, we refer to soil moisture classes (SMC) based on Petersen (1952), Koska (2001) and Joosten et al. (2015). SMCs are defined by the long-term median water table in the wet and in the dry season (see Online Resource 2). The main classes used in this study are 6+ very wet, 5+ wet and 4+ very moist.

Estimation of greenhouse gas fluxes

The analysis of GHG fluxes was literature based. However, there are no direct flux measurements from cropping paludiculture sites that cover growth and harvest cycles. Instead, we estimated GHG fluxes of each paludiculture type using the closest greenhouse gas emission site type (GEST). GESTs are based on a meta-analysis of emission measurements from a wide range of central European peatland sites (see Online Resource 3). They focus on vegetation types, which reflect ecological site conditions, like water table depth/soil moisture class (SMC), nutrient availability, acidity and land use (Couwenberg et al. 2011). These site conditions also affect GHG fluxes and render vegetation a good proxy for GHG emissions (Couwenberg et al. 2011). Each type of paludiculture has a targeted vegetation and associated SMCs and we assigned emission values of the most similar GESTs. It is assumed that annual aboveground biomass increment is harvested each year and that the fluxes represent soil fluxes only. Positive fluxes denote net emissions to the atmosphere. As direct measurements of actual paludiculture sites are missing, values are indicative best estimates.

For calculating global warming potential (GWP in CO_2eq), we used a factor 28 for methane (CH_4) (Myhre et al. 2013). GHG fluxes presented here are site fluxes. We did not include emissions from machinery during management as they are considered to be negligible (Emmer and Couwenberg 2017). Both drainage-based and 'wet' agriculture enclose emissions from machinery; paludiculture is potentially less labour intensive as sites would be harvested at most once a year without further working of the land. Furthermore, emissions by grazing livestock were not included. Nitrous oxide (N_2O) was not considered, as N_2O emissions are erratic in their occurrence and hard to assess, matter mainly on drained peatlands and are negligible after rewetting (Couwenberg et al. 2011). No GHG emissions were estimated for forestry-based paludicultures as the measurement of GHG fluxes on wooded sites is complicated (Tiemeyer et al. 2013) and reliable data therefore scarce. For comparison, we also included GHG fluxes for drainage-based land use using emission factors from National Inventory Reporting (UBA 2020).

Derivation of paludiculture eligibility classes and assessment of potential greenhouse gas emission reductions

A cross-sectoral spatial planning approach for paludiculture has previously been developed in a multi-stakeholder discussion process in the German federal state of Mecklenburg-Vorpommern (Tanneberger et al. 2020b). Here, we modify and extend this approach to the North-German federal states of Brandenburg, Lower Saxony and Schleswig–Holstein. Vector data maps on the scale of the respective federal state on peatland/organic soil distribution (Tegetmeyer et al. 2020) served as a basis for eligibility maps for paludiculture. First, the organic soil polygons were clipped down to polygons of agricultural land use (Mecklenburg-Vorpommern, Brandenburg and Lower Saxony: field parcel scale; Schleswig–Holstein: higher aggregated data due to access restrictions), to only include areas currently under agricultural use. Second, we identified areas currently under nature protection and attached this information to the polygons of organic soils under agricultural use. Depending on protection status, restrictions may exist concerning modification of the present vegetation. To consider these restrictions, we distinguish between 'permanent grassland paludiculture' and 'cropping paludiculture' (Tanneberger et al. 2020b). In cooperation with the relevant regional authorities, we assigned protected areas such as nature reserves, national parks, protected landscapes, biosphere reserves and Natura 2000 sites to paludiculture eligibility classes. We used four classes (Tanneberger et al. 2020b):

- Class 1: any paludiculture is possible;
- Class 2: permanent grassland paludiculture is possible but cropping paludiculture only after an administrative assessment;
- Class 3: only permanent grassland paludiculture is possible and an administrative assessment is needed to safeguard nature protection goals;
- Ineligible (Class 4): area is not eligible for paludiculture.

Depending on the approach of the authorities, the eligibility of the same type of protection status differs between federal states (see Nerger & Zeitz 2021 for details). For example, some federal state authorities assumed that cropping paludiculture is not compatible with permanent grassland protection and thus only eligible on current cropland or that paludiculture in general is not eligible in protected areas of the European Union (i.e. Natura 2000 sites). This may be reconsidered and harmonised in the future. The Geographic Information System software QGIS 2.18 as well as ArcMap 10.3 (for Lower Saxony: ArcGIS Version 10.5.1.) were used to compile the spatially explicit data on soil types, agricultural land use and protected areas. All geodata were either publicly available on geoportals or provided by federal state authorities.

The resulting paludiculture land classification was then used to assess potential emission reductions in a land use change scenario that follows the Paris Agreement and the IPCC 1.5 °C (2018) report, i.e. along a pathway towards net zero CO_2 emissions at around 2050 (Abel et al. 2019; Tanneberger et al. 2021), for one federal state (Brandenburg) serving as an example. Following this pathway, we assume for 2030 that land use continues on all currently used peatlands, that cropland use on drained peatlands ceases and is largely replaced by cropping paludicultures and that 85% of the total area has a SMC of 3 + or 4 + and 15% a SMC of 5 + or 6 + (see Online Resource 2).

Assessment of biodiversity effects

After rewetting, in all types of paludiculture, biomass will be harvested by mowing or grazing. Both are likely to have a significant effect on biodiversity. As paludiculture is not established on a large, commercial scale in temperate Europe yet and biodiversity studies on pilot sites are rare, we conducted a literature review. In total, we reviewed 177 sources (peer-reviewed studies but also unpublished reports and assessments; see Närmann et al. 2021 and Online Resource 4). In a subset of 82 sources from managed sites, we specified positive, positive and negative, and negative effects of paludiculture on abundance and diversity within different species groups. Furthermore, we incorporated the results of a workshop held in March 2019 with 32 experts on different aspects of biodiversity and from various peatland regions in Germany. We were careful in drawing conclusions as in most studies, near-natural managed (mown or grazed), wet areas are compared with near-natural unmanaged, wet controls. In contrast, future paludiculture will largely concern previously drained, intensively used and rewetted sites.

Assessment of business economics

To analyse the economic viability of different types of management, potential costs, revenues and profits from different sources were compiled. For this purpose, both standard data sets (KTBL 2005, 2018) and special data sources and literature (e.g. Kaphengst et al. 2005; Schätzl et al. 2006; Wichmann 2017; Sweers et al. 2014) were used. As some costs and revenues crucially depend on the prevailing conditions, we looked at an unfavourable, a moderately and a highly favourable case, resulting in a range of possible values in the cost and revenue scenarios. As conditions determining costs, we included, e.g. in case of wet meadow paludiculture area size, obstacles for trafficability, biomass yield, available machinery, biomass harvesting technique and biomass transport distance (see Online Resource 5). As conditions determining revenues, we included sales opportunities and payment schemes.

Results

Greenhouse gas fluxes

The GWP of the studied paludiculture types varies between 0 and 8 t CO_2eq ha^{-1} y^{-1} (Fig. 1). Paludiculture types at higher water levels emit more CH_4, but considerably less CO_2. Common Reed at SMC 6 + (summer/autumn median water table not lower than at soil surface) has the lowest GWP (0 t CO_2eq ha^{-1} y^{-1}) and the highest CO_2 uptake (12 t CO_2 ha^{-1} y^{-1}). All three paludiculture types at SMC 5 + (summer/autumn median water table not lower than 10 cm below soil surface) have a GWP of c. 6 t CO_2eq ha^{-1} y^{-1}; that of wet pastures is slightly higher (8 t CO_2eq ha^{-1} y^{-1}).

Area potential and potential greenhouse gas emission reduction

In northern Germany, there is 1,397,221 ha of organic soil (Table 1). Most of it are fen peatland/peaty soils (842,363 ha). The majority of this area is currently drained and under agricultural use (654,713 ha). Some 301,347 ha were classified as eligibility classes 2 or 3, i.e. an administrative assessment would be needed before a decision can be made to permit a certain type of paludiculture. There are also 232,597 ha classified as class 1, i.e. eligible for both permanent grassland as well as cropping paludiculture with regard to nature conservation requirements. The total area of fen peatland/peaty soils in North-Germany potentially eligible for paludiculture is 533,944 ha. Figure 2 is an example of a paludiculture suitability map for the federal state of Brandenburg.

In Brandenburg, 186,000 ha of organic soil is currently used for agriculture, of which about 147,000 ha is grassland. Potentially ~ 185,500 ha (classes 1 and 2–3) are suitable for paludiculture. In a 1.5 °C pathway similar to that in Abel et al. (2019) and Tanneberger et al. (2021b), we would assume that 156,500 ha have water tables no lower than 30 cm below the surface (SMC 4 + or 3 +) and that 28,000 ha have water levels close to or above the surface (SMC 5 + or 6 +). Annual GHG emissions from this area would amount to 1.2 to 3.1 Mt CO_2eq, as opposed to 5.5 Mt CO_2eq at present (Online Resource 5).

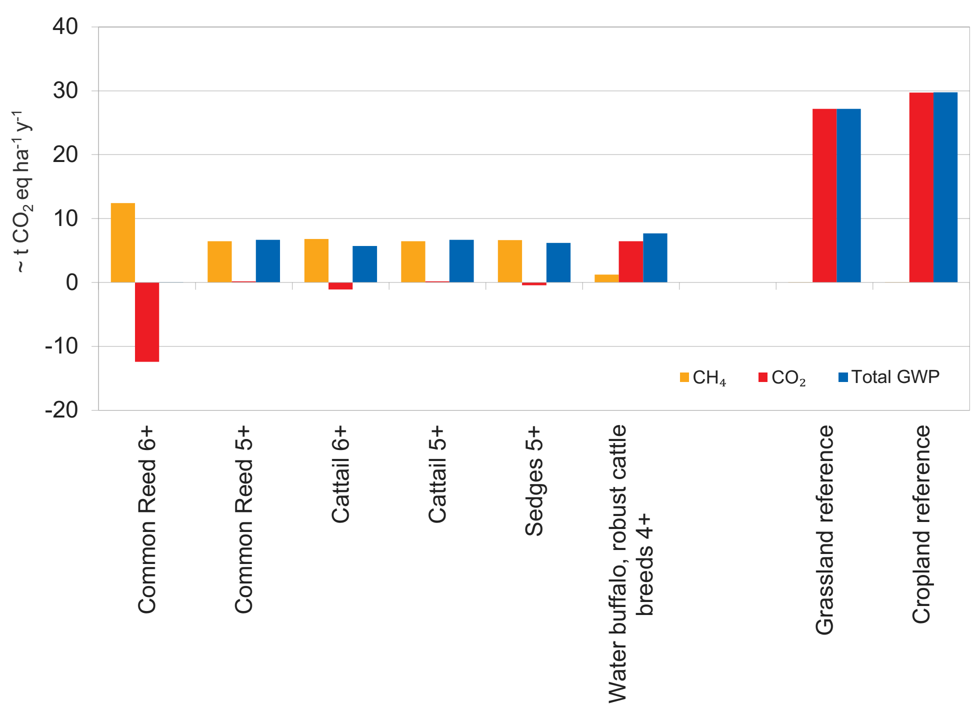

Fig. 1 Estimated CO_2 and CH_4 site emissions and global warming potential (GWP) of temperate European fen paludiculture types based on GESTs. Positive fluxes denote net emissions to the atmosphere. Due to a lack of data for woody vegetation no emission values for *Alnus* were included, even though *Alnus* is known to be peat preserving under high water tables (Barthelmes 2009). For comparison, also CO_2 and GWP (excluding N_2O) values for drained cropland and grassland based on UBA (2020) are given (see Online Resource 2 for details of soil moisture classes (6 + very wet, 5 + wet, 4 + very moist))

Table 1 Paludiculture suitability classes on agriculturally used fen peatlands/peaty soils in North-Germany (federal states Mecklenburg-Vorpommern, Brandenburg, Lower Saxony, Schleswig–Holstein)

Federal state	Total area organic soil (ha) [% of the federal state][a]	Fen area (ha) [% of the total area of organic soil]	Class 1 Any paludiculture (ha)	Class 2 Permanent grassland or cropping paludiculture (with admin. check) (ha)	Class 3 Only permanent grassland paludiculture (with admin. check) (ha)	Total potential paludiculture area on fen soils (classes 1–3) (ha)	Ineligible (ha)
Mecklenburg-Vorpommern[b]	283,650 [12.2]	~283,000 [99]	85,468	49,949	28,827	164,244	1,656
Brandenburg[c]	260,447 [8.8]	260,008 [99]	52,795	132,896		185,691	321
Lower Saxony[d]	669,065 [14.0]	168,000 [25]	~22,000	~6,000	~71,000	~99,000	~19,000
Schleswig-Holstein[c]	184,059 [11.7]	131,355 [71]	72,334	12,675		85,009	21,792
Total	1,397,221	842,363	232,597	301,347		533,944	33,769

[a]Tegetmeyer et al. (2020); [b]Tanneberger et al. (2020b); [c]this study; see Nerger and Zeitz (2021) for details; [d]recent estimate for total organic soil in 1:50,000 soil map is ~500,000 ha; values for fens excluding fens with < 30-cm peat layer; estimates for paludiculture classes: C. Beyer

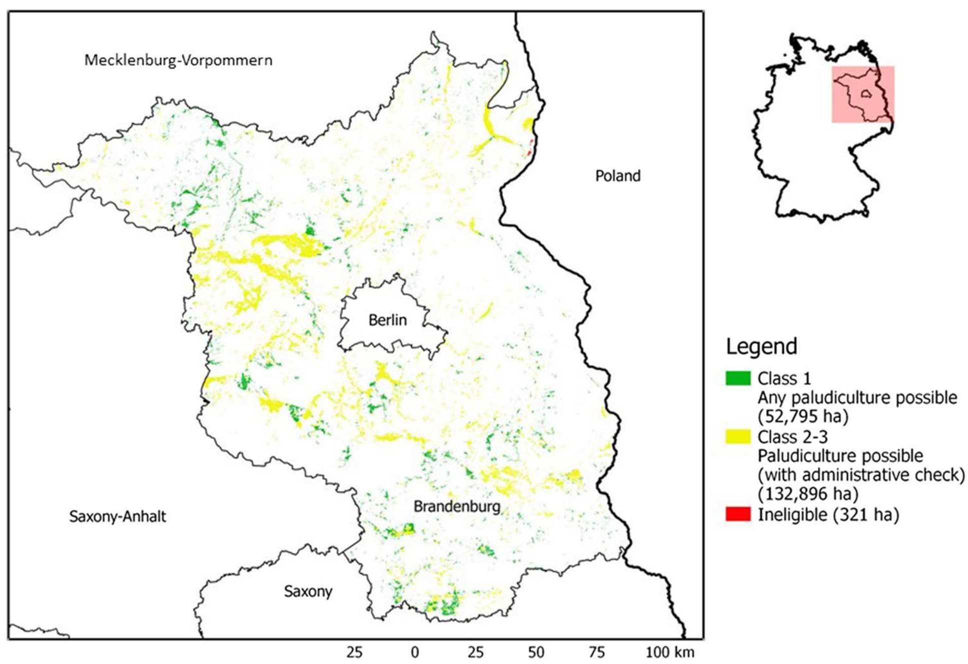

Fig. 2 Paludiculture classes for agriculturally used peatlands in the federal state of Brandenburg, Germany (see Table 1 for more details)

Biodiversity

The literature review revealed, as an overriding result, that rewetting of drained fens will lead to an increase in fen characteristic biodiversity. In both flora and fauna, a shift from xerophilic to hydrophilic species is highly likely to occur.

As the water level is a key factor determining the vegetation composition in fens (Wheeler and Shaw 1995; Jabłońska et al. 2011), rewetting will result in drastic changes in vegetation (Hellberg 1995). Species adapted to dry(er) conditions will be replaced by hygrophilic species (Richert et al. 2000). When areas are flooded (water tables above the surface), they are often rapidly colonised by Cattail (*Typha latifolia* and *T. angustifolia*) (Richert et al. 2000; Timmermann et al. 2006). With continued succession, reeds dominated by Common Reed (*Phragmites australis*) or sedges (*Carex* spec.) are likely to establish (Zerbe et al. 2013). Conflicts of interest between climate protection and biodiversity conservation can arise where rare dry habitats, which would be impaired by rewetting, have been established on drained peatlands (Dolek et al. 2014, Vischer-Leopold et al. 2015).

Also a turnover towards hydrophilic, fen characteristic fauna is highly likely. For example, in Carabidae (Görn and Fischer 2015) and Staphylinidae (Hoffmann et al. 2018), an increase in habitat specialists but also in total species richness after rewetting was observed in North-Eastern

Germany. A clear increase in fen characteristic amphibians and reptiles was reported for rewetted fens in Belarus (Kozulin et al. 2011). Especially the development of birds after rewetting is well documented. For example, Herold (2012) reports breeding bird communities of high conservation value after rewetting; critically endangered and previously lost species like *Zapornia pusilla*, *Crex crex*, *Gallinago gallinago* and *Spatula querquedula* returned as breeding birds.

The establishment of cropping paludiculture seems to promote fen biodiversity as well. In pilot sites for Cattail cultivation in Germany and Switzerland, several characteristic fen plant species were established (Pfadenhauer and Wild 2001, SIG Rohrkolben 2009). A bird survey in a 1-ha site in Switzerland yielded twelve species with suspected breeding; among them were species like *Porzana porzana* and *Acrocephalus arundinaceus* (Graf 2014).

Management by mowing or grazing reduces litter accumulation and leads to an increase in light availability and consequently to changes in microclimate (Bosshard et al. 1988; Diemer et al. 2001). Light availability is crucial for seedling establishment in fens (Kotowski and van Diggelen 2004) and litter cover impedes germination success (Jensen and Gutekunst 2003). Consequently, management of wet meadows and reed beds by mowing or grazing often results in a more species-rich vegetation (Cowie et al. 1992; Güsewell and Le Nédic 2004, Ausden 2010). A meta-analysis even found an increase of 90% in plant species richness in managed freshwater reed beds compared to unmanaged ones (Valkama et al. 2008).

With regard to fauna, management of fens by mowing or grazing promotes thermo- and heliophilic as well as open area species and phytophagous invertebrates. In other cases, management (especially mowing) impedes faunal biodiversity by directly killing or harming animals and by modifying microhabitats. Management effects are strongly taxon specific and may differ within orders or even families and between management types (Table 2). For example, cutting of Common Reed decreases characteristic reed bird species but promotes waders like *Vanellus vanellus* or *Gallinago gallinago* (Goc et al. 1997; Vadász et al. 2008). In contrast to mowing which cuts vegetation at a uniform height (McBride et al. 2011), grazed fens exhibit a greater variability in habitat structures (e.g. Zahn et al. 2010).

Business economics

Taking into account potential costs, market revenues, if applicable, additional income from current agri-environmental schemes (AES) and profits, the studied fen paludiculture types can be economically viable under moderately favourable conditions (Table 3). This is the case for wet meadows, wet pastures and harvesting of common reed for thatch. Both costs and revenues can vary considerably between favourable

Table 2 Effects (green and +: positive; yellow and +/−: positive and negative; red and −: negative, grey: not specified) of paludiculture on abundance and diversity within different species groups (meta-analysis of 82 studies, see Närmann & Tanneberger 2021). Effects of rewetting were not taken into account

	Wet meadow	Wet pasture	Common reed	Cattail
Vegetation	+	+	+	+
Aves	+	+	+/−	
Chironomidae			−	
Corixidae			−	
Thysanoptera			−	
Lepidoptera	+	+/−	−	
Hymenoptera			−	
Isopoda			−	
Araneae	+/−	+/−	+/−	
Coleoptera		+	+/−	
Aphidoidea			+	
Diptera			+	
Oligochaeta			+	
Acari			+	
Hydrophilidae				+
Orthoptera	+/−	+/−		
Mollusca	−	−	−	
Formicidae	+			
Amphibia		+		
Odonata		+		
Staphylinidae		+		

and unfavourable scenarios. Wet pastures with robust breeds are profitable in all scenarios. In a highly favourable scenario with good prices for insulating material, cultivation of Cattail offers the highest potential profit. Details of the economic assessment for one paludiculture type (wet meadows) are presented in Online Resource 6.

Discussion

Improved assessments of paludiculture emission factors and reduction potentials

We present new GHG emission factors for different paludiculture types (i.e. SMC/crop combinations) that may be used as a reference for assessing the climate effects of shifting drainage-based land use to paludiculture. GHG data are taken not only from Germany but from peatlands in temperate Europe. It can thus be assumed the results are valid for the whole region. In practice, there will be sites that emit more and sites that emit less. The GESTs used for some paludiculture types have a small underlying sample size, which means that changes in emission values by several tonnes per hectare and year may occur as science advances

Table 3 Indicative values for potential costs, revenues (incl. income from agri-environmental support) and profits of main fen paludiculture types in Germany. Values are given for moderately favourable conditions (and for unfavourable and highly favourable conditions in brackets). Summarised from Pfister and Oppermann (2021)

Paludiculture type	Potential costs (Euro/ha)	Potential income (Euro/ha)	Potential AES (Euro/ha)	Potential profit (Euro/ha)	Literature for costs and yields
Wet meadow[a]	– 200 (– 870/– 240)	330 (250/900)	320 (105/685)	450 (– 515/1345)	KTBL (2005), KTBL (2018)
Wet pasture					
Water buffalo	– 920 (–)	950 (690/1080)	235 (100, 680)	260 (– 130/840)	Sweers et al. (2014)
Robust breeds	– 600 (– 500/– 690)	1010 (1080/1215)	280 (100, 860)	690 (680/1385)	Kaphengst et al. (2005), Scholz (2019)
Common reed[b]	– 500 (– 770/– 840)	1075 (610/2380)		570 (– 160/1540)	Wichmann (2017)
Cattail[c]	– 3630 (– 4330/– 2760)	3540 (2105/5400)		– 90 (– 2225/2740)	Schätzl et al. (2006)

[a]See Online Resource 6 for a detailed, exemplary economic assessment of this paludiculture type

[b]For harvesting natural stands (no costs for planting and hydrological infrastructure included), use as thatch

[c]Costs for planting and hydrological infrastructure included; the revenues are not based on real prices, but on calculations for prices to cover medium costs

in the future. The emission factors refer to stable situations and there are considerable uncertainties about emissions during rewetting and establishment of paludiculture, as well as for emissions from ditches and (peat) dams in paludiculture settings. A near-zero exchange of CO_2 and N_2O can be assumed under wet conditions, but CH_4 emissions strongly vary spatially and temporally, and the driving parameters are not fully understood yet (Bhullar et al. 2014; Hahn et al. 2015; Franz et al. 2016; Minke et al. 2016). Despite all uncertainties and expected variations, such factors are needed in order to assess the effects of land use scenarios on organic soils. Further research is urgently needed to lower the uncertainties and increase the understanding of underlying processes.

Direct measurements are not available for complete growth-harvest cycles of cropping paludicultures and data from unmanaged systems were used as reference. Whereas emissions from rewetted sites do not differ substantially from undrained sites (Wilson et al. 2016), further research is needed whether emission factors from unmanaged peatlands can be transferred to paludiculture sites. In particular, long-term direct measurements that cover rewetting and establishment phases are needed. On the one hand, studies indicate that net fluxes from mown/grazed systems are hardly different from those of unused systems as long as water levels remain the same (Günther et al. 2015; Johnson 2016). On the other hand, there are differences because photosynthetic output declines sharply directly after harvesting, while respiration continues to take place (Koebsch et al. 2013). Yet, the mowing also stimulates plant growth and can increase the overall photosynthetic output (Herbst et al. 2013; Günther et al. 2015), depending on the time of mowing (Fogli et al. 2014). Below-ground productivity may increase in reaction to mowing as well (Luo et al. 2021). Still, the role of above-ground plant litter in the soil carbon balance may be more important than thus far acknowledged (Michaelis et al. 2020). With respect to CO_2 fluxes, the thus far available data suggest that emissions are close to zero when water tables are close to the surface (Wilson et al. 2016; Tiemeyer et al. 2020).

Very high methane (CH_4) emissions have been observed from flooded, fertilised sites (Kandel et al. 2020), as well as from sites that receive nutrients-rich organic matter through lateral inflow (Augustin & Chojnicki 2008; Minke et al. 2016) and as a result act much like ditches in agriculturally drained fields with comparable CH_4 fluxes (Peacock et al. 2021). Also, recently rewetted sites can show high methane emissions when vegetation not adapted to wet conditions dies off and provides ample easily degradable biomass for methanogenesis (e.g. Streck et al. 2017). Removal of vegetation and the topsoil before rewetting will drastically reduce methane emissions (Harpenslager et al. 2015; Zak et al. 2018; Huth et al. 2020). In contrast to rewetting for nature conservation, paludiculture management may include active water management, allowing to minimise CH_4 emissions by keeping the water table closely to the surface during the warm months.

Upscaling site emission factors to regional emission (reduction) estimates requires reliable spatial data. Data on organic soil distribution are often not up to date (Tanneberger et al. 2017; Tegetmeyer et al. 2020 for Germany). In this study (Online Resource 5), we have included the federal state of Brandenburg, as its map of organic soils has been updated more recently than that of other peatland-rich federal states (Tegetmeyer et al. 2020). A drained peat layer can disappear within decades due to accelerated decomposition, possibly enhanced by ploughing. Repeated ground verification and correction are needed at drained sites with shallow peat deposits or non-peat organic soils to reliably assess the areal extent of organic soils (Roßkopf et al. 2015). New opportunities for an improved assessment of paludiculture area potentials arise from the increased data availability provided by modern Earth observation satellites, especially Sentinel-2 (Drusch et al. 2012). The two systems Sentinel-2A and 2B deliver imagery at 10–20-m spatial resolution, 10 spectral bands and a theoretical combined observation frequency of 2–4 images per 10 days, which allow for fine-scale analysis of vegetation phenology or visible water. When combined with Landsat-8 data (Roy et al. 2014), the Sentinel 2 data has been successfully employed for national-scale grassland management characterisation including mowing event detection (Griffiths et al. 2020). Similarly, crop types and hence detailed information on agricultural land use and cover can be derived over large areas and on an annual basis (Griffiths et al. 2019). Metrics derived from such time series have only recently been shown to contribute to an assessment of rewetted surfaces (Kreyling et al. 2021), as spectral indices change significantly when water levels surpass soil/vegetation. In combination, the different possible information levels will further help in a wall-to-wall mapping of the status of rewetted fens.

Outcomes of regional scenarios for future agricultural use on organic soils such as presented in Table 2 vary strongly according to the underlying assumptions. Here, we assume a substantial proportion of the land to be managed under moist or very moist conditions. This may allow for stepwise adaption of farms to higher water levels (Tanneberger et al. 2021). A recent report on climate neutrality of agriculture in Germany argued that omitting the ‘moist’ stage may be a better solution for many farms, especially for those using cropland (Grethe et al. 2021).

Improved assessments of biodiversity effects and business economics of paludiculture

In the past, rewetting was carried out mainly for the restoration of biodiversity, which is also reflected in the studies included in the literature review (Online Resource 4). Untouched peatlands rightly served as a reference (e.g. Dijk et al. 2007; Klimkowska et al. 2007; Herold 2012). The biodiversity of rewetted, mown or grazed paludiculture fens should, however, not be compared with that of near-natural fens. Rather, the status prior to rewetting, mostly intensively used grassland or arable land, in Eastern-European countries also peat extraction sites in fens, should be used for comparison. Large-scale drainage from the 1960s onwards led to the extinction of fen mire biodiversity typical of Central Europe (Succow 2001). The drained fens are intensively used as grassland and arable land and are of low ecological value (Klimkowska et al. 2010). Rewetting and cessation of high-intensity land use will certainly lead to a significant improvement compared with the current status. Whereas evidence for plants and birds is available from various studies, invertebrate taxa and other organism groups have been insufficiently studied so far. A major information deficit is also seen in the potential effects of wet pastures and cattail cropping paludiculture on biodiversity. Generally, the studies to date have largely investigated either rewetting or management of fen sites. However, both processes must be considered together in the case of paludicultures, and in our study, we provide such a combined insight applicable not only to Germany, but also to other temperate fen peatlands in Europe. Biodiversity monitoring should be carried out on all paludiculture demonstration sites, and wherever possible be compared with the status prior to rewetting.

For many forms of paludiculture, there are still data gaps with regard to costs and revenues. Even for the relatively widespread wet meadows, where much detailed information is available, there is still a lack of information on which site conditions and biomass yields are most frequently encountered on paludiculture sites in practice. Yet, site conditions and characteristics like area size, firmness of the soil, unevenness of the soil, frequency of obstacles and distance from the farm in combination with biomass yields determine the machinery that can be used, the necessary labour input, and the resulting costs and revenues. Therefore, several scenarios should be calculated. Point estimates of profitability are easily miscalculated and deterministic accounting using fixed values is restricted to specific cases. Simulations demonstrating the conditions and the possible range of loss or profit are likely to provide a more accurate picture of reality (Wichmann 2017). Also, potential income from agri-environmental schemes substantially affects the outcome, and future funding frameworks need to be considered carefully.

Recommendations for enhancing biodiversity in fen paludiculture and fair remuneration

The intensification of agricultural practices in recent decades has led to a substantial loss of biodiversity in the agricultural landscape (Tscharntke et al. 2005; Donald et al. 2006; Stoate et al. 2009). Our review has shown that rewetting of drained fens and implementation of paludiculture is very likely to enhance fen biodiversity compared to the previous drained condition. The following measures should be applied as standard in paludiculture in order to avoid stepping into the same pitfalls conventional agriculture has stepped into in the past (Närmann and Tanneberger 2021):

- Abstain from nitrogen or phosphate fertilisation
- Abstain from insecticides
- Abstain from tillage and turning of the soil

- Biodiversity-enhancing design and maintenance of ditches.

To enable the full potential of biodiversity restoration and conservation, biodiversity-promoting measures in wet fen management can be pursued. Such measures can both enhance positive effects and mitigate inhibiting factors. Possible measures in fen paludiculture include (Närmann and Tanneberger 2021):

- Establishment of 1-year rotational fallows
- No rolling, dragging and harrowing in spring before mowing
- High cut of at least 8 cm
- Use of cutting (oscillating) instead of rotating mowing technology
- Bird breeding time restrictions

Measures to promote biodiversity often incur additional costs that need to be met. Biodiversity-promoting measures that receive payments exist already on mineral soils, e.g. use of special equipment (Pfister and Oppermann 2021). If we want the ecosystem services of wet peatlands and paludiculture to benefit society, we need to remunerate them generously and clearly beyond a reimbursement of costs. Farmers must see their own advantage in providing ecological services (Hampicke 2018). In the end, wet peatland management is only interesting for the farmer if the sum of revenues (biomass sales, direct payments and agri-environmental support) significantly exceeds total costs. A long-term prospect of substantial net income for the farmer is a prerequisite for large-scale implementation.

Towards large-scale implementation of paludiculture

Until now, rewetting has largely focussed on areas of high interest for nature conservation but little interest in terms of land use (Barthelmes et al. 2021). To comply with the Paris Agreement, a much stronger emphasis must be placed on rewetting deeply drained peatlands/organic soils currently under high-intensity land use (Greifswald Mire Centre et al. 2020; Tanneberger et al. 2021b; Grethe et al. 2021). These deeply drained lands have a high potential for climate change mitigation (Tiemeyer et al. 2020), but rewetting them currently still incurs large opportunity costs (Buschmann et al. 2020). Implementing paludiculture can reduce these opportunity costs if it is supported by strong public incentives and investments. Current agri-environmental support is not sufficient to make paludiculture interesting and lack of incentives obstructs large-scale roll-out (Tanneberger et al. 2021b; Grethe et al. 2021). Based on our analysis, key recommendations are (i) to provide planning security for land users by extending and refining spatial planning for paludiculture, (ii) to initiate the establishment of the pilot and best practice demonstration sites with special attention to decentralised solutions to address the large variety of environmental and socio-economic conditions and (iii) to strengthen research into paludiculture crops, water tables and management options to optimise climate and other environmental effects and economic consequence.

These results are in line with the summary of recommendations for large-scale implementation of paludiculture by some 200 scientists and practitioners during the globally largest paludiculture conference in 2017 (RRR 2017). Here, also additional recommendations that reach further into societal and political dimensions were presented, e.g. (i) adjustment of legal frameworks, including stopping incentives which maintain or stimulate peatland drainage, and ensuring accounting for emissions from organic soils under the Paris Agreement; (ii) provision of financial incentives from the public sector (e.g. for rewetting and investments, payments for ecosystem services), and improved access to finance, and (iii) stimulation and support of innovation along the entire paludiculture value chain, including breeding, cultivation, harvesting, transport and processing technologies, logistics, economy and markets (RRR 2017).

Paludiculture is a new, future-orientated concept for the sustainable use of peatlands (Joosten et al. 2016b; Wichtmann et al. 2016). The fen paludiculture types presented in this article are probably only the beginning of multiple possibilities in temperate Europe. Methods to assess GHG emissions, biodiversity effects and indicative business economics of paludiculture are suggested and discussed, and ways to arrive at a large-scale implementation of paludiculture are indicated. The large-scale implementation of paludiculture requires a consequent and consensually pursued paradigm change. The solution of problems that originate from drainage-based peatland utilisation will depend decisively on political will and successful best practice examples (Wichtmann et al. 2016; Tanneberger et al. 2020b).

Supplementary information

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