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EDITED BY
Sate Ahmad,
Trinity College Dublin, Ireland

REVIEWED BY
Carsten Paul,
Leibniz Center for Agricultural Landscape Research (ZALF), Germany
Florence Renou-Wilson,
University College Dublin, Ireland

*CORRESPONDENCE
Sabine Wichmann
✉ wichmann@uni-greifswald.de

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Unlocking the potential of peatlands and paludiculture to achieve Germany's climate targets: obstacles and major fields of action

Sabine Wichmann[1,2]* and Anke Nordt[1,2]

[1]Chair of Landscape Economics, Institute of Botany and Landscape Ecology, University of Greifswald, Partner in the Greifswald Mire Centre, Greifswald, Germany, [2]Institute of Sustainable Development of Landscapes of the Earth (DUENE E.V.), Partner in the Greifswald Mire Centre, Greifswald, Germany

Greenhouse gas emissions from drained peatlands must be substantially reduced to meet climate mitigation targets. In Germany, annual peatland emissions of 53 Mt CO_2e account for more than 7% of total national GHG emissions. Peatland drainage and reclamation is traditionally considered as a symbol of progress and technical achievement, where agriculture has been the major driver. In Germany, an area of 1.3 million ha of drained peatlands used for agriculture ought to be rewetted by 2050 to meet the 1.5°C target of the Paris Agreement. Paludiculture allows a productive use of wet peatlands instead of abandonment following rewetting. This approach might therefore pave the way for voluntary large-scale peatland rewetting. However, implementation remains scarce. The long history and large extent of peatland drainage has shaped the political and legal framework as well as perceptions and attitudes, thus impeding rewetting and climate-friendly peatland use. This policy and practice review investigates the political, legal, economic and social aspects that hinder the implementation in Germany and derives approaches to overcome multifold restrictions. Finally, three major fields of action are identified: (1) To increase and accelerate rewetting, a consistent peatland mainstreaming approach is needed that overcomes structural barriers and adapts the policy and legal framework, e.g., the Common Agricultural Policy, planning law, water law and nature conservation law. (2) To motivate for a rapid transition, a system of immediate, comprehensive and attractive positive incentives is needed. This should be accompanied by early announcement and gradual introduction of negative incentives to set a clear course and provide planning certainty for farmers and landowners. (3) A just transition depends on empowering local communities to develop and pursue perspectives tailored to their peatland region. Future research of peatlands as social-ecological systems can help to identify region-specific drivers for sustainable peatland management.

KEYWORDS

paludiculture, rewetting, agricultural policy, legal framework, peatland mainstreaming, transformation, just transition, path-dependency

1 Introduction

Peatlands may form where the annual rate of decomposition is lower than the rate of plant biomass production, due to water-saturated (anoxic) conditions, leading to the accumulation of organic material in the form of peat (e.g., Rydin and Jeglum, 2013; Schwieger et al., 2021). Throughout history, extended peatlands often formed traditional borders between political regions, cultures and languages due to their limited accessibility and remained widely unexploited, unsettled wilderness areas for a long time (Silvius et al., 2008). About 85–90% of the global peatlands are still in a natural state (Joosten, 2016; Leifeld and Menichetti, 2018). In Europe, however, only 54% of the present-day peatland area, and in Germany less than 2%, are covered by peat forming ecosystems (Tanneberger et al., 2017). Large-scale and systematic drainage took place in recent centuries, usually because social elites and political authorities incentivized, prescribed, and finally organized peatland reclamation – often in time of crisis and wars (Wichmann, 2021). Laborious drainage "conquered" new land for settlements by inner colonization (Von Knobelsdorff-Brenkenhoff, 1984) and turned peatlands into productive dry land used for peat extraction, agriculture, and forestry. The drainage and reclamation of peatlands were considered a symbol of progress, technical achievement and prerequisite for the rural development of less developed, sparsely populated, peripheral regions (Blackbourn, 2006).

The biased focus on "conquering wasteland" for productive use has long ignored, or at least outweighed, the destructive effects of drainage-based peatland use on biodiversity and ecosystem functioning (Wichmann et al., 2016a). In Germany, the early descriptions of various negative impacts of peatland cultivation date back up to 200 years. In the 19th century, buckwheat cultivation using fire was opposed because of health harming smoke, overexploitation, and soil destruction (Berg, 2004), and already in 1910, the "Zehlau-Bruch" peatland was recognized and protected as a natural monument since it was a rare example of a pristine mire (Steinecke, 1919). The role of peatlands for the landscape water balance and the warning against large-scale drainage was emphasized by Jaekel (1922). The repeated process of drainage, subsidence and deepening of the drainage level became known as the "vicious circle" (Kuntze, 1983). Finally, nutrient and carbon cycling gained attention during the last decades with increasing knowledge on ecosystem functioning and biogeochemical processes in wet and drained peatlands.

The global climate crisis changed the perception of peatlands - both in science and policy. It was recognized that the thick peat layers with concentrated carbon, which formed over thousands of years, constitute the largest organic carbon store of the terrestrial biosphere (UNEP, 2022). Clear scientific evidence became available that drainage turns a long-term carbon sink into an enormous source of greenhouse gas (GHG) emissions. Protecting wet peatlands *and* restoring drained peatlands were identified as key for climate change mitigation (Humpenöder et al., 2020). In contrast to protecting selected peatlands for biodiversity conservation, every single peatland becomes important in light of the climate crisis (Barthelmes et al., 2015). Recent national peatland strategies in Europe reflect the challenge of climate change and aim at protecting peatlands, i.e., areas with peat soils, as carbon stores (Nordbeck and Hogl, 2024). Raising the mean annual water level depth greatly reduces greenhouse gas emissions from drained peatlands without necessarily abandoning their productive use (Evans et al., 2021). Rapid action and prompt rewetting are required (Günther et al., 2020) to contribute to the target of net zero CO_2 emissions by 2050 (IPCC, 2018) derived from the Paris agreement on limiting climate warming to well below 2°C (UN, 2015).

Europe is a global hot spot of human impact on peatlands and the second largest emitter of GHG emissions from drained peatlands, after Indonesia (UNEP, 2022). Within the EU, Germany has the highest share of drained peatlands (about 95%) and the highest GHG emissions (UNEP, 2022). In many European countries, agriculture is the major driver for peatland drainage. Drained peatlands hold a low share of agricultural land (EU: 2.7%, DE: 7%), but are responsible for a disproportionally high share of the total agricultural GHG emissions (EU: 27%, DE: 40%; Martin and Couwenberg, 2021). Agriculturally used peatlands are complex, social-ecological systems. Increased knowledge of the ecological subsystem with the water level depth as the key biophysical driver has been insufficient to initiate large-scale peatland rewetting.

This policy and practice review focuses on the social subsystem of peatland management. For the case of Germany, it provides a first comprehensive overview on various obstacles to peatland rewetting and land use adaptation to raised water levels. The paper identifies political, legal, social, and economic drivers of change and discusses major fields of action to contribute to Germany's climate targets (Figure 1). Since peer-reviewed literature is scarce, the review draws mainly on legal documents, practical experience of implementing paludiculture pilot projects (Supplementary Table), stakeholder discussions, and a large variety of grey literature. Reports, guidelines and briefing papers were reviewed that provide valuable insights based on practical experience, extensive expert interviews or stakeholder workshops but are published neither peer-reviewed nor in English. In contrast to a case-study approach, we collected relevant aspects across different projects and regions in Germany to provide a comprehensive as possible and sufficiently detailed coverage of the current situation and discussion on sustainable peatland management. At this general level, we aimed at a "theoretical saturation," i.e., the point when new material did not bring additional factors. This mapping of obstacles and solutions can inform and inspire more detailed investigations of specific peatland cases. Though the focus is on Germany, many of the identified aspects either relate to the wider scale of European regulations or can be transferred to the situation in other countries.

2 Potential of peatlands to achieve climate targets in Germany

German emissions from peatlands and other carbon rich soils (organic soils) amount to annually 53 Mt carbon dioxide equivalents (CO_2e); this corresponds to more than 7% of Germany's total emissions (UBA, 2022). Splitting up the emissions from organic soils, carbon dioxide (CO_2) accounts for the largest share (91%) while nitrous oxide (N_2O) and methane (CH_4) play a minor role (Tiemeyer et al., 2020). Therefore, mitigation measures need to primarily target CO_2 (Tiemeyer et al., 2020). Prompt rewetting is required despite potential increase of strong but short-lived methane emissions (Günther et al., 2020). The majority of the peatland area in Germany is used for drainage-based agriculture (71%) emitting 42 Mt CO_2e annually, followed by forestry (15%), and peat extraction (2%) (UBA, 2022). Rewetting all drained peatlands used for agriculture in

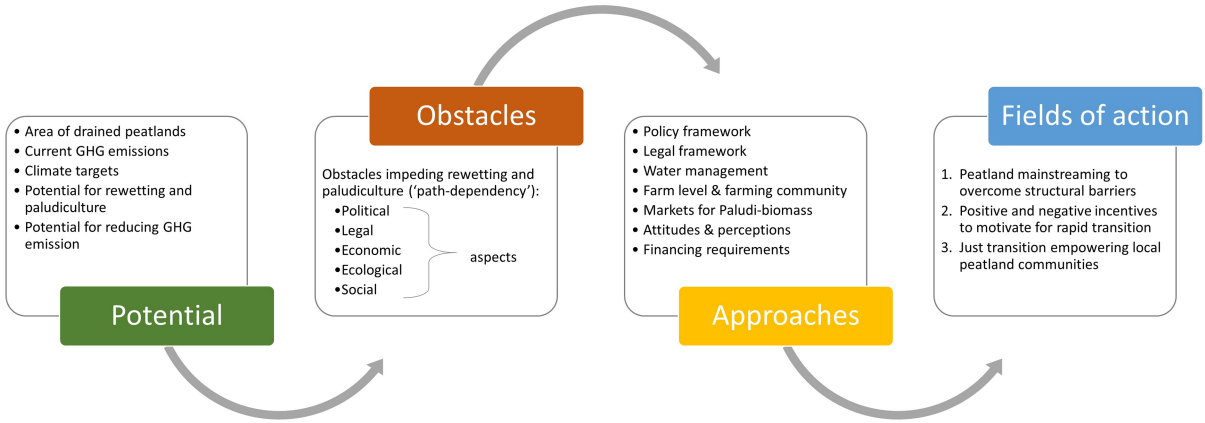

FIGURE 1
Working steps of this study estimating the potential of peatlands to achieve climate targets, identifying obstacles to rewetting and paludiculture, deriving approaches to overcome these obstacles and selecting major fields of action.

Germany would reduce annual emissions by more than 30 Mt CO_2 (Tanneberger et al., 2021).

Climate protection targets are set at different political and legal levels. The Paris agreement is the first legally binding UN treaty on climate change defining the overarching goal to limit global warming to well below 2°C above pre-industrial levels, and to aim for 1.5°C (UN, 2015). The EU has made a legal commitment to be climate neutral by 2050 (European Climate Law, European Parliament, and Council of the European Union, 2021a). In addition, the EU has set specific carbon sink targets for the Land Use, Land Use Change and Forestry (LULUCF) sector with the Fit for 55 program, which targets a 55% GHG reduction by 2030 (European Climate Law, Schlacke et al., 2022). Within the LULUCF sector, emissions from peatlands are reported together with carbon sequestration in forest and wood products. The carbon source caused by peatland drainage is thereby hidden by the carbon sink function of forests. The EU level target for carbon removal is −310 Mt CO_2e per year by 2030. In Germany, the LULUCF sector shall be an increasing carbon sink of −25; −35; −40 Mt CO_2e per year by 2030; 2040; 2045, respectively (German Federal Climate Change Act, German Federal Parliament, 2021). So far, emissions from peatlands have been compensated by the carbon sink effect of forests. Projections see a decrease of this sink function, with the LULUCF sector becoming a net source of CO_2e emissions in Germany by 2025 (BMU, 2021a). This increases the pressure to reduce emissions caused by peatland drainage.

Germany aims for GHG neutrality by 2045 (German Federal Climate Change Act, German Federal Parliament, 2021). Additionally, several federal states have set their own climate targets; e.g. the peatland rich states Mecklenburg-Western Pomerania, which aims for GHG neutrality by 2040 (SPD, and DIE LINKE, 2021), and Lower Saxony by 2045 (Lower Saxony, 2022). These targets require the comprehensive reduction of GHG emissions from organic soils, including peatlands.

Next to general climate and sectoral targets in legal documents, peatland specific targets are defined in national strategy documents. According to the Federal and States Target Agreement on Climate Protection through Peat Soil Protection (BLZV, 2021) and the National Peatland Conservation Strategy (BMU, 2021b), annual emissions from drained peatlands have to be reduced by 5 Mt of CO_2e by 2030, which corresponds to around 10% of current emissions. For this purpose, the governmental projection report specifies 224,260 ha of agriculturally used peatlands for grassland extensification combined with a rise in water levels and 80,600 ha for complete waterlogging of previous grassland areas (BMU, 2021a). In addition, peatland emissions in Germany are addressed in state peatland protection concepts of the peatland-rich states of Bavaria, Brandenburg, Mecklenburg-Western Pomerania, Lower Saxony and Schleswig-Holstein (Ewert and Hartung, 2020).

In line with the CO_2 reduction pathway to meet the 1.5°C target (IPCC, 2018), a peatland transformation pathway represents a scenario of net zero CO_2 emissions from peatlands by 2050 (Abel et al., 2019; Tanneberger et al., 2021). The scenario refers to the need to minimize all sources within each land use category on peatlands, which in this case means raising the water table on a total of about 1.8 million ha of organic soils in Germany. On average, more than 50,000 ha of organic soils will have to be rewetted every year between now and 2050 (Tanneberger et al., 2021). Other analyses derive reduction targets for CO_2 and other emissions from drained peatlands in Germany of 7–20 Mt by 2030 (18–35.8 Mt by 2050; Günther et al., 2019; Öko-Institut, 2019, 2021; Tanneberger et al., 2021). The area indicated for a water table rise ranges from around 200,000 ha (Prognos, Öko-Institut, Wuppertal-Institut, 2020) to 741,400 ha (Tanneberger et al., 2021) by 2030, and 650,000 ha (Öko-Institut, 2019, 2021) to 1,457,600 ha (Abel et al., 2019, Tanneberger et al., 2021) by 2050. The wide range of estimates for rewetting and emission reduction reflects the discrepancy between (a) what is considered a realistic potential based on the current political situation and the principle of voluntary implementation in opposite to (b) what would be needed to achieve the climate targets. Apart from the major differences in objectives, the current implementation with an estimated area of about 2000 ha per year (Barthelmes et al., 2021) does not meet even the lowest projections of about 20,000 ha per year (e.g., Prognos, Öko-Institut, Wuppertal-Institut, 2020).

The concept of paludiculture, the productive use of wet and rewetted peatlands, has been developed for more than two decades, aiming to accelerate peatland rewetting while maintaining land use with site adapted plants and management in order to sustain income

for farmers and landowners (Joosten et al., 2015a,b; Wichtmann et al., 2016). However, the implementation of paludiculture has so far been very limited. Based on an international survey, Ziegler et al. (2021) describe paludiculture as an emerging and science-driven innovation that faces strong adverse path-dependency from drainage-based peatland use. Path-dependency describes the fact that past decisions affect present decisions and may provide obstacles and resistance to following a new path. The following section summarizes predominant obstacles to peatland rewetting and paludiculture in Germany.

3 Obstacles to rewetting and paludiculture

The long history and large extent of peatland drainage have shaped the political and legal framework as well as perceptions and attitudes in Germany. Thus, a variety of obstacles encompassing political, legal, economic, ecological, and social aspects hinder the implementation of climate-friendly peatland use. The relevant aspects are (1) *overarching external* aspects (e.g., policy and legal framework), (2) *regional external* socio-economic and ecological aspects of the wider surroundings or (3) *internal* aspects at farm-level and within the peatland area (Figure 2). The core unit of implementation are land parcels with peat soils embedded in a peatland area and a wider environment. Two situations need to be distinguished: "Type A," the landowner is also the land user of the parcel, or "Type B," the land user leases the land and two entities – the land user and the landowner – need to be addressed concerning decisions on raising water levels and adapting land use. Furthermore, most peatland areas consist of many land parcels with different owners and different land users, which all need to be involved in the negotiations. Both rewetting and productive use in the form of paludiculture represent a paradigm shift in peatland management compared to the widespread drainage-based productive use. Manifold obstacles to rewetting and paludiculture were identified and grouped into seven categories. Major obstacles are explained in the following sections and constitute the basis for deriving solutions how to address and overcome obstacles in chapter 4 (Tables 1–7) and identifying major fields of actions in chapter 5 (Figure 1).

3.1 Overarching external aspects

3.1.1 Policy framework

Due to its area-wide effectiveness, the EU's Common Agricultural Policy (CAP) and its national implementation has the greatest impact on current peatland use. The CAP defines minimum farming standards (conditionality), grants direct payments per hectare (Pillar I) and supports voluntary environmental and climate measures (Pillar II). Subsidies under Pillar I and Pillar II of the CAP continue to be fully available for drainage-based use of peatlands in the new funding period that started in 2023. While a new minimum standard for maintaining good agricultural and environmental conditions (GAEC 2) has been introduced to protect wetlands and peatlands, its effectiveness depends on how the new conditionality is nationally implemented. In Germany, arable use of peatlands may continue, minimum water levels are not addressed, renewing drainage infrastructure to lower the existing drainage level requires permission with agreement of local nature conservation and water authorities; but deeper drainage is not forbidden (§10 GAPKondG, §13 GAPKondV, BMEL, 2022). Public payments for

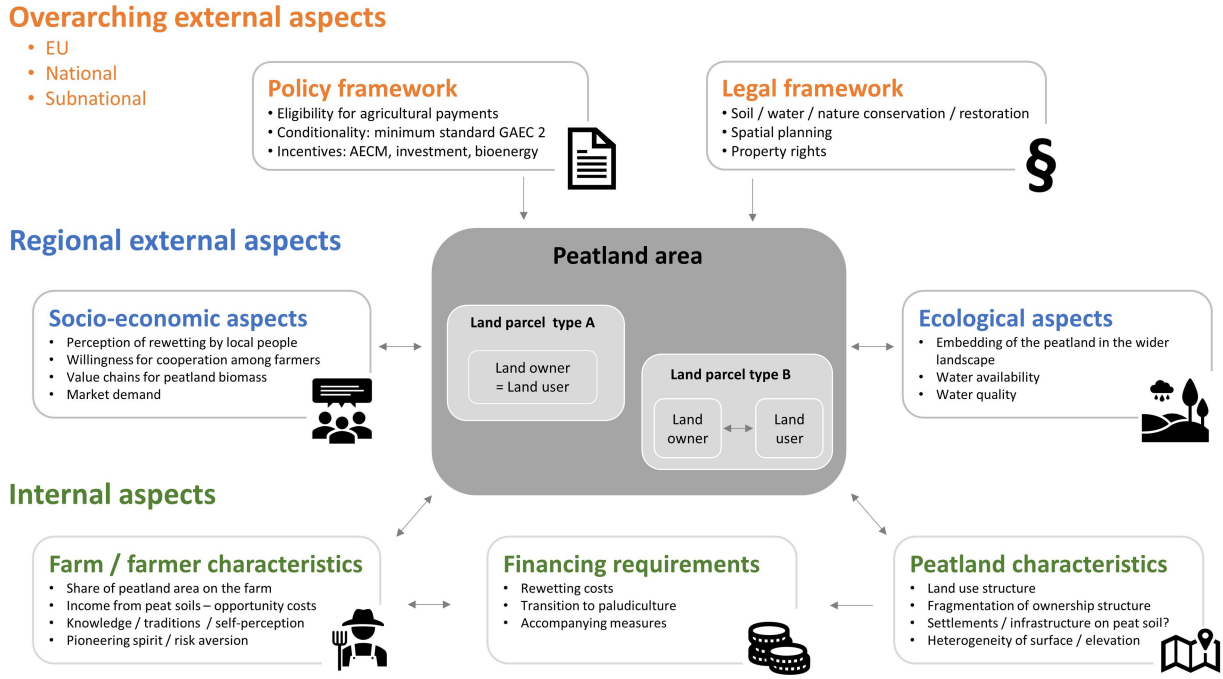

FIGURE 2
Peatlands need to be understood as complex social-ecological systems with overarching, external and internal aspects influencing the land use of every single land parcel.

TABLE 1 Obstacles to peatland rewetting and the implementation of paludiculture due to current policy, approaches to reducing obstacles, and level of action.

Policy framework		
Obstacle	Approach	Level of action
Lack of coherence between agricultural and climate policy	Review and re-orientate agricultural and structural support toward climate change objectives	EU, national, subnational
	Earmark funds for climate change only on the basis of quantifiable climate change contributions	EU, national, subnational
The agricultural legislative framework does not support rewetting of peat soils	Deliver higher minimum standards for peat soil protection via conditionality (GAEC 2)	EU, national
	Use organic soil map for minimum standards (and as basis for funding schemes)	National, subnational
Wrong incentives for maintaining drainage	Establish direct eligibility for paludiculture as agricultural activity; Wet grassland: no penalties for inundation and occurrence of wetland species.	EU, subnational
	Phase out direct payments for drainage-based peatland use	EU, national
	Exclude drained peatlands from any AECM payments that do not address high(er) water levels	National, subnational
	Prevent lock-in effects through peatland criteria in investment funding provisions and long-term support schemes (e.g., renewable energy)	National, subnational
Missing incentives for wet land use	Reward high water levels (measure) and / or services for climate, soil and water protection (result-orientated)	EU, national, subnational
	Provide funding for advisory service and investments to support transition to paludiculture	EU, national, subnational

TABLE 2 Obstacles to peatland rewetting and implementation of paludiculture due to current legal framework, approaches to reducing obstacles, and level of action.

Legal framework		
Obstacle	Approach	Level of action
Legal framework not compliant with peatland strategies and climate policy targets	Peatland mainstreaming: define fields of action and set priorities	EU, national, subnational, municipal
	Define good practice for peatland use and implement legal security	National, subnational
	Allow derogation of grassland protection (GAEC 1, GAEC 2, GAEC 9, federal state laws) for wet peatland use	EU, national, subnational
	Integrate peatlands in spatial planning as priority areas for nature-based climate protection	National, subnational, municipal
Costly and time intensive approval processes	Facilitate water law to accelerate approval procedures, e.g., by declaring water retention and climate protection being of public interest	National, subnational
	Consolidate areas in public hand (e.g., in land agencies) to buffer adjacent rewetting effects and liability risks, and to provide areas for land exchange	National, subnational, municipal
	Provide guidelines for approval authorities, applicants, planning offices	Subnational
	Provide funding for surveys and approval planning	EU, national, subnational
	Increase staff capacity (most of all within approval authorities)	Subnational, municipal
Risk of nature conservation requirements / lack of incentives for voluntary measures	Define regulations on the establishment and harvesting of protected species / biotopes	National, subnational
	Compensate for crop or yield losses resulting from unforeseeable or incalculable nature conservation restrictions	National, subnational
	Create additional financial incentives for voluntary measures to promote biodiversity	National, subnational
Property rights include the right to drainage	Incorporate peat soil features in tenancy law / public land lease standards	National, subnational, municipal
	Establish a fund to cover compensation / damage payments to reduce liability risk conflicts	National, subnational

climate-damaging peatland use continue to set wrong incentives, turning the "polluter pays" principle upside down (Schäfer, 2016). Furthermore, payments for drained peatlands affect the competitiveness of paludiculture and frustrate pioneers.

A major obstacle to large-scale implementation of paludiculture is the risk of losing the land's eligibility for agricultural payments. Farming wet peatlands and growing paludiculture plants has not been considered as agricultural activity cultivating agricultural products, despite centuries of productive use (e.g., reed for thatching) (Kölsch et al., 2016; Geurts et al., 2019). The decisive factor for the recognition as an agricultural product eligible for subsidies is the classification in the EU tariff schedule and which chapters of this nomenclature are listed in Annex I to the Treaty on the Functioning of the European Union (TFEU, European Union, 2012). Chapter 14, which is not listed

TABLE 3 Obstacles to peatland rewetting and implementation of paludiculture due to water management and water availability issues, approaches to reducing obstacles, and level of action.

Water management and water availability		
Obstacle	Approach	Level of action
Complex hydrological planning	Building capacity in planning and permitting institutions, improve coordination and cooperation between involved parties, e.g., via local "peatland stewards"	National, subnational
	Expand scope and capacities of water boards	National, subnational, municipal
	Identify target areas for rewetting	National, subnational
Active water management necessary	Strengthen role, mandate and capacities of water boards	National, subnational, municipal
Risks: water shortage, nutrient supply	Roll out research and development program on water management and plant production aspects	National, subnational
	Identify (and prioritize) suitable areas	subnational
Restriction of property rights and third party usage rights when rising water levels	Consolidate areas for climate action measures	Subnational, municipal
	Make use of experience from acquiring land for flood protection measures	National, subnational
	Promote cooperative approaches at water catchment area	National, subnational

TABLE 4 Obstacles to peatland rewetting and implementation of paludiculture due to operational aspects at farm level and the social environment, approaches to reducing obstacles, and level of action.

Farm level and farming community		
Obstacle	Approach	Level of action
Necessary paradigm shift	Promote self-image and role model of peatland climate farmers (pioneers)	National, subnational
	Provide or backup risk coverage (e.g. with public guarantees)	subnational
Opportunity costs vary widely	Develop advisory concepts for farm conversions	National, subnational
	Use of tendering procedures for the efficient distribution of funds	National, subnational
	Set up Paludi-farm networks	national
High initial investments, lack of effective rewarding instruments	Compensate costs and risks of conversion to paludiculture	National, subnational
	Strengthen cooperation models between farmers (e.g. machinery rings) and along the biomass processing chain	subnational
	Integrate paludiculture into eco accounting and compensation	subnational
Lack of long-term plant cultivation experience	Increase funding for long term research, development and demonstration projects	National, subnational
Lack of knowledge	Provide farmers with information on the local distribution and characteristics of peat soils	subnational
	Establish training and further education on wet peatland utilization	National, subnational
	Promote knowledge transfer and demonstration sites	National, subnational

in Annex I, contains references to, *inter alia*, trade in reeds, rushes and leaves of cattail species as plaiting materials (product code 14019000), i.e., common paludiculture products that are therefore considered non-agricultural products. The recent CAP reform aims to address this obstacle from 2023 onwards: "Agricultural land should not be excluded from the granting of direct payments if it is cultivated with non-agricultural products by means of paludiculture within the framework of EU schemes contributing to one or more environmental or climate-related objectives of the Union" (Regulation (EU) 2021/2115, European Parliament, and Council of the European Union, 2021b). However, in the definition of "agricultural activity" (Article 4, 2 a), eligibility is further limited to those paludiculture crops that produce "agricultural products" as defined in Annex I to the TFEU (European Union, 2012). This is *de facto* no improvement compared to the previous funding period; high-value paludiculture plants such as reed and cattail are still excluded. However, derogations have been extended that qualify for a continued receipt of direct payments for previously eligible areas that no longer meet the eligibility criteria. In this context, paludiculture with the production of non-Annex I products and in combination with national measures for GHG reduction or biodiversity, is explicitly mentioned as an exception (Article 4, 4 c, ii) (Regulation (EU) 2021/2115, European Parliament, and Council of the European Union, 2021b). The lack of clear, practical guidelines for paludiculture crops and the associated risks discourage not only peatland farmers. Agricultural administrations and authorities are also reluctant, or at least uncertain, to promote paludiculture.

Single approaches to raise water levels and to adapt farming has been funded in some peatland rich EU Member States (Wichmann, 2018; Chen et al., 2023). German examples encompass the agri-environmental-climate measure "peat conserving water retention (fixed weir)" via the CAP's Pillar II (European agricultural fund for

TABLE 5 Obstacles to peatland rewetting and implementation of paludiculture due to lack of utilization and demand for biomass from paludiculture, approaches to reducing obstacles, and level of action.

Markets for biomass from paludiculture		
Obstacle	Approach	Level of action
Little experience, new product chains	Set up living labs on paludiculture	National, subnational
	Promote product development	National, subnational
High investment costs for processing plants	Provide investment funding programs for biomass utilization	National, subnational
	Draft guarantee programs for business loans	Subnational
	Consider peatland emissions balances within the Building Energy Act	National
Lack of market admission, patents, life cycle analyses, lack of market access	Simplify product admission during market introduction phase	National
	Provide funding for product admission tests	National
	Introduce specifications for public building projects / procurement for the use of Paludi-products (e.g. building materials, growing substrates) to stimulate market access	National, subnational, municipal
	Promote communication and information of target groups	National, subnational
	Incorporate environmental and climate impact performance into product pricing	National
	Mission oriented industrial policies	European, national

TABLE 6 Obstacles to peatland rewetting and implementation of paludiculture due to reservation of land users, land owners and local people, approaches to reducing obstacles, and level of action.

Attitudes and perceptions		
Obstacle	Approach	Level of action
Approval for peatland drainage, focus on food production	Improve knowledge and strengthen appreciation for the provision of ecosystem services	National, subnational
	Improve appreciation of material and energy utilization of agricultural commodities	National
Planning uncertainty and institutional complexity	Extend funding programs long term	National, subnational
	Apply declining funding schemes	National, subnational
Fear of material depreciation and loss of quality of life	Include climate relevance in land value assessment	National
	Provide early communication about projects and opportunities for participation	National, subnational, municipal

rural development, EAFRD) and investment grants for harvesting machines suitable for wet peatlands with low bearing capacity as well as funding for research and demonstration on paludiculture (European Regional Development Fund, ERDF) (Wichmann, 2018; Hirschelmann et al., 2020, *cf.* chapter 4.7). Those first incentives to support climate change mitigation through peat soil protection, however, are outbid by the continued support for drainage-based peatlands, including the financially attractive combination of basic payment, eco-schemes, and agri-environment-climate schemes available for drained grasslands. Thus, peatland farmers have strong economic incentives to proceed with on-going drainage. In addition, 5–7 year funding periods fail to provide long-term planning security for conversion to paludiculture (Wichmann, 2018; Abel et al., 2019). Furthermore, not all peatland-rich regions or countries provide voluntary schemes for wetter peatlands within the new EU funding period, neither in Germany (BMEL, 2023) nor in other member states (BirdLife Europe, and EEB, 2022). While the conversion to paludiculture is not feasible without the use of CAP instruments ("the key policy to become the 'game changer' for peatlands in the EU is the CAP", Tanneberger et al., 2020a), further obstacles related for instance to legal aspects, knowledge gaps or underdeveloped markets need to be overcome to convince farmers.

In addition to area-based payments, other incentives have an even longer lasting impact. Agricultural investment grants and funds from ERDF and national programs support investments in, e.g., new stables for animals or new drainage infrastructure. Long term secured feed-in remuneration for bioenergy is given via the Renewable Energies Act (EEG, German Federal Parliament, 2014) and supports the production of maize and grass silage on drained peatlands. These incentives lead to lock-in-effects as they manifest production systems based on peatland drainage for long depreciation periods of the investment.

3.1.2 Legal framework

Parallel to the EU legislation on agricultural subsidies, there is a need for action in the national regulatory framework to facilitate climate change mitigation in the land use sector. Setting the CAP minimum standards "Protection of wetland and peatland" (GAEC 2) too high, would have several draw backs: (a) farms cannot be rewarded for implementing basic agri-environmental-climate measures, (b) the risk of "opting out" increases, i.e., farms foregoing agricultural subsidies

TABLE 7 Obstacles to peatland rewetting and implementation of paludiculture due to financing requirements, approaches to reducing obstacles, and level of action.

Financing requirements		
Obstacle	Approach	Level of action
High upfront costs for conversion to paludiculture, insufficient operating liquidity for high initial investment	Fund programs for climate measures on peatland, farm conversions, downstream biomass processing and product demand	National, subnational
	Establish a (national) emission trading system (ETS) for peatland emissions; include LULUCF or the land sector in an ETS	National
	Establish a CO_2 pricing system	National
	Nudging transformation through Carbon Contracts for Difference (BMWK, 2023, prerequisite: CO_2 price applies to agriculture/land use)	National
	Provide public land for pilot and demonstration projects	National, subnational, municipal
Insufficient financing	Involve funding from different governance levels and private financing for peatland transformation	EU, national, subnational
Complex funding environment	Advisory offices for overarching information on all funding options for rewetting and paludiculture, including different public funds (EU, national, subnational) and private financing	subnational
Restrictions by laws on state aid	Find solutions to avoid double funding to enable interaction of different funding options, e.g., combining public and private schemes; allow income effect to incentivize climate action	EU, national, subnational

in order to escape the requirements, e.g., biogas farms growing maize on drained peat soil, (c) from a political economy perspective, Latacz-Lohmann et al. (2019) raise concerns that the implementation of high environmental standards via GAEC risks permanently cementing direct payments. In contrast, minimum standards should be applicable to all peatland parcels independent of CAP subsidy provision. In Germany, the main starting point is the definition of good agricultural practice in the Federal Soil Protection Act (BBodSchG, German Federal Parliament, 1998). So far, the law does not reflect that peat soils have special characteristics and other needs for protection compared to mineral soils. The lacking definition of good practice for the management of peat soils has been emphasized for more than ten years (LABO, 2011; Abel et al., 2016; LABO, 2017; Wichtmann et al., 2018). Obstacles connected to regulatory law are a lengthy reform process and expected enforcement problems due to control deficits.

Next to permanent grassland paludiculture with a vegetation established by succession, a targeted establishment of wetland species like Common Reed, Cattail, Reed Canary Grass or *Sphagnum* mosses (cropping paludiculture) can be combined with peatland rewetting (Tanneberger et al., 2020b). The maintenance of permanent grassland is required, however, by European subsidy law (GAEC 1, GAEC 2 and GAEC 9; in the past cross-compliance, greening) and in addition by subnational law in some federal states. Grassland in general is expected to provide environmental benefits and in particular the sequestration of carbon. This neglects once more the differences between organic and mineral soils. It is not the type of use (arable land vs. permanent grassland) that determines the carbon footprint of organic soils, but the water table. The requirements for grassland conservation (permit requirement, establishment of replacement grassland, ban on conversion in Natura 2000 areas) prevent the conversion of often deeply drained peatland grassland into more sustainable permanent paludiculture, although this land use change would contribute to climate, water, and biodiversity protection (Czybulka and Kölsch, 2016; Peters and Von Unger, 2019; GMC and DVL, 2021). The obligation to create a replacement area by converting arable land into new grassland represents a very large additional obstacle and financial burden for farms, but at the same time is associated with relatively low benefits for climate and biodiversity protection. The German soil condition survey found equally high carbon losses for grassland as for arable land on organic soils; only raised water levels protect the soil carbon (Jacobs et al., 2018). In paludiculture pilots, the CAP grassland protection requirement led to opting out, i.e., giving up the agricultural land status and thus waiving agricultural payments (Supplementary Table; GMC and DVL, 2021).

Numerous requirements under water and nature conservation law, and partly also under building law, have to be complied with when raising water levels and establishing paludiculture (Czybulka and Kölsch, 2016; Martinez et al., 2022; Peters and Schäfer, 2022). The applications and documents required for the approval process depend heavily on the regional authority responsible and the protection status of the area (*cf.* Supplementary Table). Implementing large-scale rewetting projects requires complex planning approval procedures, including hearing procedures for the participation of specialist authorities and the public (Hasch, 2016). Therefore, rewetting cannot be carried out by individual farms, but only with the involvement of competent project management agencies and services (planning offices). Approval procedures are costly and time-consuming with long lead times (5–10 years). The difficult case-by-case assessments typically arise from a lack of clear guidelines on how to deal with conflicting objectives and a lack of prioritization. For example, the Water Framework Directive targets water retention as well as ecological continuity of watercourses and according to the Federal Water Resources Act (German Federal Parliament, 2009b) water retention in peatlands to mitigate climate change is currently mostly classified as water course development (Hirschelmann et al., 2023).

As near-natural peatlands and wetlands have become very rare in Germany, the few remaining near-natural habitats and their characteristic species are predominantly subject to nature conservation legislation (Schopp-Guth, 1999). According to Annex I of the EU Habitats Directive, the proportion of protected peatland habitat types is just under 7% of the total peatland area in Germany (Ssymank and Scherfose, 2012). However, many of these areas do not have near-natural water levels and are therefore not in a peat-conserving condition and do not represent natural peatland habitats. As rewetting

measures usually affect the condition of protected (non-peatland) habitats and species, there may be conflicts with the objectives of the EU Habitats and Birds Directives (Ssymank et al., 2015). Many peatland farmers have major concerns about additional nature conservation requirements related to rewetting and paludiculture and fear restrictions on or a ban of harvest. Paludiculture might be restricted because of the targeted cultivation and harvesting of protected species (e.g., *Sphagnum* moss), the classification of paludiculture areas as protected biotopes (e.g., reed beds), and if protected species colonize paludiculture areas as replacement habitats.

Legal obstacles to paludiculture are also related to civil law, especially lease agreements (Schäfer and Yilmaz, 2019). The conversion to paludiculture changes the requirements for the leased land. For some paludiculture crops, such as cattail, the necessary hydraulic changes require a change in the contractual modalities of the lease. In addition to the change in use, the rent might also need to be adjusted. Furthermore, the liability risk due to impairment of neighboring areas in case of water logging might be an issue of civil law conflicts as for example legal actions for damages.

3.2 Regional external and internal aspects

3.2.1 Operational aspects at farm level and social environment

Paludiculture is uncharted territory for farms and society. There is a lack of practical experience, of showcases for demonstration, and long-term research at farm-level and thus of knowledge. Open questions on plant cultivation concern, for example, stand management, the occurrence of calamities, nutrient supply and long-term yield development. Compared to drainage-based peatland farming, technically and economically consolidated production methods and reliable standard data for cost calculations are not yet available for paludiculture (Wichmann, 2016). Soil degradation caused by peatland drainage and options for permanent wetland use have so far been largely absent in professional and academic training, further education and consulting (Abel et al., 2019). The necessary paradigm shift in peatland management to work with water, not against water, represents a break with family or farm traditions. Over decades and centuries, land reclamation by drainage had a positive connotation. Pressure to justify rewetting can be expected within the family, within the local community and within the profession. Farms establishing paludiculture need a pioneering spirit and a willingness to change and take risks.

Farm opportunity costs and constraints can widely differ depending on the farm-specific situation, as for instance the importance of the drained peatlands within the farm and thus the possibility of entry into paludiculture. A cash crop farm that has to lease grassland on peatlands along with the leased arable land, even though it has no use for the biomass, can immediately agree to raise the water level without affecting the farming business. A dairy farm located entirely on peatland and with the recent investment in a new, large dairy cowshed is committed in the long term to the production of high-quality fodder on all land and requires a transition period for developing a new business case. Farm opportunity costs depend strongly on the added value of the current use, e.g., cereal or maize production or vegetable cultivation vs. extensive grazing (Röder et al., 2015; Ferré et al., 2019), and also on agricultural payments (Rebhann et al., 2016). The total farm area and the share of peatland area also play a role. For instance, for small farms with high value vegetable farming it is especially difficult to integrate new practices (Ferré et al., 2019). High-value niche paludiculture like cultivating herbs, medicinal or ornamental plants could be an alternative. In a comparative study on socio-economic and business environments in six European peatland regions, Buschmann et al. (2020) identified "hard economic variables" such as the level of income from peatland cultivation and (quasi-)market incentives as decisive for preferred land use alternatives and the acceptance of rewetting.

The high initial investment for conversion to paludiculture is a large obstacle for individual farmers. Investment needs may include land preparation, crop establishment, infrastructure for water management and logistics, and specific harvesting equipment. Depending on the crop, the first income from the new permanent culture can only be achieved after several years (Wichmann, 2016). Specialized technology adapted to the low bearing capacity of wet peatland soils is available and has been tested on a large scale, especially for reed harvesting, and landscape management (Wichmann et al., 2016b). However, buying special technology and making full use of it requires several hundred hectares of wet peatlands or setting up a cooperation between farms for sharing machines (Dahms et al., 2017). One of the main obstacles toward sustainable peatland farming has been the lack of operational instruments to reward the high social benefits of conversion to paludiculture, despite the recognition of wet peatlands as nature-based solutions (Tanneberger et al., 2020a).

3.2.2 Utilization and demand for biomass from paludiculture

While enterprises farming drained peatlands may produce for instances milk, meat, potatoes, or cereal for existing markets, paludiculture farmers face the challenge how to develop new product chains and get market access. There is a high demand for high-value uses, such as cattail for building and insulation materials, reed for roofing or *Sphagnum* moss biomass as an alternative to peat for growing media in professional horticulture, but there is currently a shortage of cultivation sites (Krus et al., 2015; Becker et al., 2020; Wichmann et al., 2020). On the other hand, heterogeneous biomass from wet meadows is available but not used or used for low-value energy production (combustion, fermentation). In some cases, the areas are too small or too fragmented for economic size of processing plants (logistics costs), the heat sink is too small, and the biomass is not very transportable. Innovative processes for material utilization from fibers are still in the pilot and establishment phase. These gaps between supply and demand are known as the chicken and egg problem. Obstacles encompass high investment costs for setting up decentralized biomass processing or utilization plants (heating plant, panel plant, etc.), few existing cooperation structures as well as missing certificates, patents, and life cycle analyses for marketing climate-benefits of paludiculture products.

3.2.3 Water management and water availability

Rewetting of individual areas is technically possible, e.g., limited by property borders instead of organic soil extension. "Wet islands in drained landscapes" (see pilots in Supplementary Table) are, however, expensive in terms of both construction and management costs. These "wet islands" require specific investments in infrastructure for water retention and irrigation while securing drainage of sites surrounding the wet island. At the same time, these rewetted sites face water losses due to lateral and vertical seepage as well as higher evapotranspiration because of the oasis effect. Large-scale rewetting reduces the proportional implementation and management costs. Against this

background, a cooperative catchment-based approach is required, involving overarching hydrological planning and cooperation between different land users, landowners, and neighboring landowners. However, the processes are complex and time-consuming (*cf.* legal framework). There is a lack of involvement and human capacity in existing organizations, such as water boards, that could take on the coordination and the water management as well as in approval authorities. Obstacles to rewetting include the high proportion of leased land, i.e., both land user and landowner must agree (Figure 2), obligations from rental agreements, fragmented ownership, and the impact on neighboring land, buildings or infrastructure on peat soil. Water scarcity and diverging claims on water utilization, e.g., for irrigation of agricultural crops, maintenance of river navigability, water framework targets on ecological continuity or water retention in peatlands for climate change mitigation need to be addressed at regional level. In the case of paludiculture, a targeted water management needs to be planned. Water scarcity as well as water quality, i.e., too few or too many nutrients, risks productivity loss and can impact the development of target species and biomass quality (Haldan et al., 2022; Vroom et al., 2022; Käärmelahti et al., 2023).

3.2.4 Reservations of land users, land owners and local people

The intention to restore higher water levels in peatlands is frequently a source of conflict. People in peatland rich regions often consider the melioration efforts of past and current generations as an achievement that should not be abandoned (Ziegler, 2020). There is also a reluctance to abandon existing farming traditions combined with a preference for livestock and food production over biomass production for material or energy uses. In Switzerland, Ferré et al. (2019) identified a strong regional identity with vegetable farming and the intensive production perceived as best valorization of organic soils. On the other hand, the acceptance for paludiculture is often higher than for abandonment. Some farmers could imagine wet farming, but express concerns about investment risks, the economic viability of paludiculture and a loss of land value. Questions concern a cost-covering and effective harvest despite the existing technical challenges of special machinery as well as customer structure, producer prices, and markets. Major obstacles are the lack of planning security and the institutional complexity, including nature conservation regulations. The word rewetting has already become an irritant in some regions. Residents fear disadvantages ranging from the loss of material values (e.g., loss of property value, which has been common after rewetting) to perceived impairment of the quality of life (e.g., mosquito plague, wet basements, inaccessibility of local recreation areas or loss of familiar landscapes; Kleinhückelkotten and Neitzke, 2016). Whether or not fears and perceptions hold true is case-specific and can be subject to change (e.g., Byg et al., 2017; Dworrak and Kiel, 2023).

3.2.5 High costs for preparatory activities and investment

Individual farmers cannot bear the high costs of preliminary studies, hydrological reports, planning and approval procedures, especially for rewetting larger areas. Further costs are related to land purchase, land exchange and / or compensation for the acceptance of a rise in water level. Land prices that are often significantly higher than the yield value of the land greatly affects a possible conversion to paludiculture. At farm level, there is high investment requirement for the conversion of farms to wet farming methods, including infrastructure for raising water levels and water management, species establishment, adapted harvesting machines, logistics and processing facilities. Compensating only for higher cost or losses occurring due to peatland management with raised water level can neither provide positive incentives for farmers nor reflect additional risks. The implementation of R&D pilots and demonstration projects is hampered by requesting high private shares from involved practitioners. The funding environment is getting increasingly complex and laws on state aid restrict the combination of different public funds (e.g., investment support, agricultural payments) as well as private financing (e.g., carbon certificates).

4 Approaches: addressing and overcoming obstacles

Based on the outlined obstacles, a wide range of approaches can be identified to overcome restrictions to peatland rewetting and the implementation of paludiculture. There is no one-size-fits-all solution. Instead, a set of complementary measures need to be taken in different areas and at different political and administrative levels. These include adapting the current policy and legal framework, regulatory approaches, and accompanying measures such as implementing research and development projects, training specialists at all levels, as well as providing financial incentives. Tables 1–7 provide an overview of suitable approaches to reduce and remove existing obstacles and indicate the respective level of action responsible for advocating and enforcing change. Examples are given for selected approaches in the following sections. Future in-depth analysis of potential limitations, synergies and trade-offs of the outlined measures and instruments are essential and call for interdisciplinary and case specific research.

4.1 Policy framework

To overcome the lack of coherence between the climate policy objectives of the EU and Member States and the incentives provided by EU funds, an alignment is needed across all sectors (Table 1). A review of all new and existing EU legislation with a view to reaching GHG neutrality has been announced as "climate mainstreaming" (European Commission, 2022a). Funding programs should follow the rules of the EU taxonomy, i.e., they should contribute significantly to at least one of six environmental objectives: (1) climate change mitigation; (2) adaptation to climate change; (3) sustainable use and protection of water and marine resources; (4) transition to a circular economy; (5) pollution prevention and control; and (6) protection and restoration of biodiversity and ecosystems (Regulation (EU) 2020/852, European Parliament, and Council of the European Union, 2020). In addition, a Do No Significant Harm (DNSH) principle has been included in EU funds regulation for 2021–2027, to prevent financing with negative environmental effects. Program holders need to check their funding programs against the EU Taxonomy classification system, to ensure that none of the six environmental objectives is significantly impaired (Levarlet et al., 2022). The CAP does not yet mention this principle. At the same time, the EU taxonomy will affect farming enterprises and companies along the whole value chain

directly via sustainability reporting and redirecting capital flows toward sustainable investments (see section 4.5).

All farms receiving direct payments must comply with minimum standards of good agricultural and environmental condition (GAEC). An ambitious design of the new conditionality on the protection of carbon-rich soils would reduce the opportunity costs of paludiculture for farmers. Whether GAEC 2 is the right instrument to implement the requirement for a gradual increase of improvement of standards until effective protection is reached (GMC and DVL, 2020; Tanneberger et al., 2021), is debatable. However, even the minimum protection of all organic soils (no deterioration) (GMC and DVL, 2020) would require higher ambitions at national level. Since any drainage causes a successive degradation, a ban on "amelioration measures" such as the creation or the renewal or deepening of drainage systems or trenching and deep plowing, is required. The reference level for "deepening" needs to be the elevation, i.e., height above sea level, and not the subsiding surface level. Although the current GAEC 2 sets very low minimum standards, it raises the awareness for peat soil protection by requiring all member states to provide detailed maps on the distribution of organic soils. Including this geodata in the GIS based system used for agricultural payments allows any farmer to determine if the plots on the farm include carbon-rich soils. The geospatial data can be also used to define the area eligible for peatland specific voluntary measures, e.g., eco-schemes and agri-environmental-climate measures (AECM).

Agricultural land use in Germany is largely determined by the CAP and agricultural subsidies. Eligibility for subsidies is therefore a basic prerequisite for the large-scale implementation of paludiculture. Any kind of cultivation for food, fiber, or energy on rewetted peat soils should directly become eligible for direct CAP payments (Geurts et al., 2019) to overcome current uncertainties related to the newly introduced derogation option in Article 4, 4c, ii Regulation (EU) 2021/2115 (European Parliament, and Council of the European Union, 2021b) (see above, section 3.1). The general definition of paludiculture as agricultural activity would be a clear statement for climate protection on agriculturally used peatlands. Cotton and short rotation coppice are already explicitly mentioned despite not being agricultural products according to the definition "products listed in Annex I of the TFEU" (Article 4, 2a Regulation (EU) 2021/2115, European Parliament, and Council of the European Union, 2021b). A similar clear regulation at EU level followed by implementation in national law seems indispensable, since German federal states do not exercise room for maneuver "on their own" (Ewert, 2019), in accordance with the guiding principles of German administrative action and cooperative federalism (Ewert, 2019; Ewert and Hartung, 2020). In addition to EU CAP, further incentives need to be adjusted or introduced at EU, national and subnational level, for example investment support (Table 1, section 4.7).

4.2 Legal framework

The legal framework needs to be adjusted from EU to municipal level (Table 2) to reduce obstacles for peatland rewetting and contribute to climate mitigation. Regulations under command-and-control law, e.g., via the Federal Soil Protection Act (BBodSchG, German Federal Parliament, 1998), can be implemented without precisely depicting GHG emissions as control variable which might limit the application of economic instruments (Ekardt et al., 2020). Another important approach is spatial planning which coordinates conflicting spatial and land use objectives. The German Spatial Planning Act (ROG) regulates the general requirements, which include climate protection and climate adaptation (§2 ROG, German Federal Parliament, 2008). With adopting the Act Amending the Spatial Planning Act and Other Provisions (ROGÄndG, German Federal Parliament, 2023) in 2023, specifications are required in regional spatial development plans concerning "open spaces to ensure natural climate protection, in particular for peatland preservation and peatland protection" (§13 ROGÄndG, German Federal Parliament, 2023). Regional planning authorities can designate priority areas in spatial development plans to protect degraded peatlands from, e.g., building developments, as this would prevent a future rise in water levels. Priority areas could be designated for peat soils where rewetting would take precedence over other conflicting uses (Martinez et al., 2022). Further regulatory changes are planned, e.g., with the protection of restoration and conservation areas through a new "Demand for land law," and several regulatory changes to speed up planning and approval, e.g., in water, soil, conservation law, are recommended by Mohr Advocates (2023).

If species or habitats have established on degraded peatlands which are protected by national or European law but actually are atypical for wet peatlands, these areas may not be rewetted until a replacement has been created on another suitable site, which poses additional pressures on site availability, project costs and complexity (Hirschelmann et al., 2023). In order to realize synergies with nature conservation targets and avoid conflicts in peatland rewetting projects, nature conservation must move away from the goal of mandatory, site-specific conservation of every single stock of a habitat type or every single population of a species in the area (Martinez et al., 2022). To do so, indicators and clear guidelines on how to prioritize and balance protected assets are necessary to minimize trade-offs. Future national restoration plans, e.g., to implement an upcoming EU Nature Restoration Law, might serve for this task and underline for the case of peatland rewetting the priority of species and habitats typical for wet peatlands.

The conversion to paludiculture may also be subject to nature conservation restrictions, such as the limitation to grassland paludiculture and the exclusion of cropping paludiculture according to the legal protection status of the area (Tanneberger et al., 2020b). Concerning biotope protection by the federal nature conservation law (§30 BNatSchG), a distinction should be made between natural stands and deliberately established stands, for instance for reed beds and sedge-dominated meadows. In the case of a 10 ha cattail site established 2019 in Mecklenburg-Western Pomerania (Supplementary Table), the right to harvest without nature conservation permission is ensured with reference to the claw-back clause [BNatSchG §14 (3) and §30 (5)]. In the case of the Sphagnum farming area in the Hankhauser Moor (Supplementary Table), a marketing permit for deliberately cultivated *Sphagnum* moss and sundew was requested due to the unclear legal situation. The Lower Saxony Water Management, Coastal and Nature Protection Agency (NLWKN), after consultation with the Lower Saxony Ministry of the Environment, certified that such a permit was not necessary as the protection under §7, 2, 13 c BNatSchG only applies to wild populations (German Federal Parliament, 2009a). Where legally protected species colonize paludiculture areas, conservation management or targeted maintenance measures for the benefit of these species might be useful. For the planning security of farmers, it must be ensured, that such

measures are not prescribed by restrictions but undertaken on a voluntary basis and - depending on the impact - financially rewarded.

In order to simplify time-consuming approval procedures under water law, professionals from practice and authorities name various "soft" options that could be implemented within the existing legal framework, but which are subject to interpretation by individuals in approving authorities. These include (a) making use of administrative discretionary powers, e.g., with decrees by supreme authorities; (b) referring to existing old water rights, which initially granted permission for, e.g., building weirs to keep a certain water level (sufficient for rewetting due to the subsidence that took place in the meantime); (c) authorities of protected areas ordering approval-free measures; and (d) better cooperation and networking between the authorities involved to reinforce conjoint goals and shorten lead time of approval procedures (Hirschelmann et al., 2023). Furthermore, a fundamental simplification of approval procedures under the water law is necessary, e.g., through legal anchoring of new or modified approval procedures, or a new legal standard of a "peatland climate protection project" category, e.g., in the Federal Water Resources Act or Federal Climate Change Act, which currently does not exist (Hirschelmann et al., 2023). The definition of peatland climate protection measures as watercourse maintenance for water retention (instead of watercourse development) are also mentioned by peatland restoration experts to simplify procedures, as well as the option to facilitate an approval procedure with expropriation effects, which already exists as corporate land consolidation in traffic infrastructure planning procedures. Another approach would be to design peatland climate protection as a state task and to create or expand appropriate enforcement bodies (Hirschelmann et al., 2023). Accelerating water law approval procedures is a key bottleneck for the implementation of peatland climate protection and paludiculture. Without the adaptation of the legal framework, neither existing nor new funding instruments will be able to develop their full effectiveness.

4.3 Water management and water availability

Climate change causes region-specific changes in precipitation and can increase water scarcity. At the same time, peatland rewetting is not only a measure for climate change mitigation but also for adaptation. Water retention and storage stabilizes the landscape's water balance, reduces the impact of floods and droughts and leads to local cooling. Delaying peatland rewetting will increase difficulties to achieve water levels near surface (Ahmad et al., 2021).

In Germany, water and soil associations (WBVs) are the key actors in area-based water management. The tasks of WBVs are listed in §2 of the Water Associations Act and include groundwater management and water supply (German Federal Parliament, 1991). However, the management goals need to be actively extended to encompass water retention in the wider landscape and to restore the hydrological buffer function of peatlands. This also needs a new understanding in the WBVs. In particular, this means recognizing that peat conservation, i.e., water levels near-soil surface, are required in peat soils (Abel et al., 2017). For the extension of tasks, WBVs need a (stronger) mandate from its members and legislator, as well as additional funds for staff. In general, capacity building (e.g., local "peatland stewards"), cooperative approaches and land consolidation are crucial to overcoming obstacles related to water management at the landscape level (Table 3). To identify target areas for peatland protection measures, using indicators of constraining as well as enabling factors can help to derive the prospects for implementation and potential maximum (climate) effect (Koppensteiner et al., 2023). This is especially relevant when capacities and funds are limited. Suitability maps for paludiculture, based on area specific conservation status, can support decision making on which type of paludiculture is permitted (Tanneberger et al., 2022).

4.4 Farm level and farming community

Table 4 summarizes major approaches to improving perception, knowledge and funding of paludiculture and peatland rewetting. Setting the frame for a new role model and job profile of "peatland climate farmer" helps to appreciate the work of pioneers, the provision of ecosystem services and the production of climate friendly renewable resources by farmers managing wet and rewetted peatlands (Stüber et al., 2023). Regional peatland (climate) protection agencies should be established to provide advice, further training, build on acceptance for rewetting and wet peatlands and support implementing measures taken by, e.g., farmers, institutions, municipalities, and are to be backed by local stewards (BMUV, 2023). Large-scale 10-year paludiculture pilot and demonstration projects are being funded by the Federal Ministries of the Environment (four projects since 2021/2022)[1] and Agriculture (five projects since 2023/2024) to implement utilization options for wet peat soils, gain site management experience and scientific data, while also working as hubs for knowledge transfer and exchange (BMUV, 2023).

Tendering procedures can promote the provision of ecosystem services at regional level and ensure efficient use of limited financial resources. They can (but do not have to) be offered cooperatively. Agglomeration and synergy effects with simultaneous simplification of administrative procedures are advantages of cooperative approaches, as already established in the Netherlands, and particularly suitable for peatland rewetting (Latacz-Lohmann et al., 2019).

4.5 Markets for biomass from paludiculture

An insight in current overall market potential for paludiculture in Germany is given by the sustainability consultancy SYSTAIN (2023), who conducted a preliminary study on creating scalable value chains using paludiculture biomass. It was based on over 40 interviews with companies in six market sectors. Building on this potential, a network of companies was established as a "demand alliance" for paludiculture products which is focusing on overcoming the lock-in-effect of sufficient demand to initiate large-scale implementation of paludiculture and sufficient supply of paludiculture biomass to develop and invest in new production chains and products.[2] Cross sectoral knowledge transfer, e.g., with the paludi tiny house (Nordt and Dahms, 2021) and changing perceptions in the building sector toward stronger sustainability requirements help to gain interest for paludiculture biomass in renewable, climate friendly building

1 https://www.z-u-g.org/foerderung/pilotvorhaben-moorbodenschutz/projekte/

2 https://www.tomoorow.org/

and insulation products (Krus et al., 2022; DENA, 2023; Material Cultures, and Bauhaus Earth, 2023). In general, investment in processing plants, product development, and simplified market admission are key approaches to supporting value chains based on paludiculture biomass (Table 5). European and national mission-oriented industry and investment policy can increase the demand for and competitiveness of biomass as renewable resource in general and especially for paludiculture biomass, as for instance by exnovation (e.g., ban on plastic, phase out peat), sustainability reporting obligations for companies [e.g., Corporate Sustainability Reporting Directive (CSRD), Ecodesign for sustainable products regulation (ESPR)] or the EU taxonomy channeling investments into low-emission and carbon positive activities.

4.6 Attitudes and perceptions

Since peatland reclamation for food production has been perceived as progress over centuries, the identification with drainage is deeply rooted in the mind-set of land users, landowners and local people. Overcoming this path-dependency requires improving knowledge but also transforming values and relationships. New positive narratives need to be developed within peatland regions (Table 6).

Peatland farmers can be categorized as Pioneers, Skeptics, Pragmatists, and Hobby Farmers, which showcases them as a heterogeneous group and highlights the need for different approaches to foster a transformation to agriculture that works with peatlands and peatland farmers to ameliorate the climate crisis (Hünnebeck-Wells, 2023). An urgent supportive situation is especially needed for pioneers, as they are closely observed–or neglected–demonstrators to other farmers (*cf.* Fenzl and Brudermann, 2009). Pioneers are needed for innovation, but the role is not necessarily perceived as being attractive: "Pioneers are those who suffer economic ruin," stated a German peatland farmer who also works as a contractor and is a representative of the farmers' association (pers. communication, 20.06.2023).

In order to address concerns and questions of the local community, early communication about rewetting projects is necessary. Appropriate participatory formats can be used to communicate and discuss the results of hydrological studies, planned work and expected changes to the landscape, e.g., with interactive "landscape walks" (Keller and Backhaus, 2017). In addition, the financial participation of local rural communities can help to enhance local acceptance and consent, e.g., via local income, tax revenues and jobs–as experienced with wind energy projects (Leiren et al., 2020). For a transformation to rewetted peatland landscapes, this could include local biomass utilization and processing to (pre-) products as well as eco-tourism.

4.7 Financing requirements

Approaches to overcome funding barriers to the implementation of paludiculture and rewetting are presented in Table 7. These include the provision of public and private funding, valorization and monetization of ecosystem services, combining rewetting with solar energy production, as well as counseling to support individual farmers with funding administration. The German government agreed on the Natural Climate Action Program, which will provide 4 billion € until 2026 with a large share dedicated to peatlands, as one of the 10 fields of actions in the program (BMUV, 2023). Funding will include preliminary activities, planning, advice, and implementation of peatland protection measures, promotion of paludiculture through funding of investments, research and development as well as regulatory approaches to increase the demand of paludiculture resources and products (BMUV, 2023).

Beside the Natural Climate Action Program, there are EU CAP supported AECM and / or state programs in every peatland rich federal state. Funding is provided for instance for the conversion of cropland to permanent grassland, paying farmers for their acceptance of high water levels (peat conserving water retention by fixed weir), cropping paludiculture and investments. While previous funding programs and payment schemes have mainly focused on peatland restoration and biodiversity conservation (e.g., LIFE, EAFRD), the new funding programs listed in Table 8 addresses all agriculturally used peatlands and their potential for climate change mitigation.

TABLE 8 Selection of expired, existing and planned funding programs for peat soil protection and paludiculture in Germany (BB = Brandenburg, BV = Bavaria, LS = Lower Saxony, MW = Mecklenburg-Western Pomerania, SH = Schleswig-Holstein).

Measures	Main source of financing				
	EU* (EAFRD)	EU (ERDF)	National	Federal state	Private
Conversion of cropland to grassland specifically on peatlands	BV[1], LS[3]			BV[1]	
Acceptance of raised or high water level	BB[2], LS[3], MW[4], SH[5]		x**	SH[10], BV[1]	BB[12], MW[12]
Deliberately establishing wetland plants (cropping paludiculture)	BB[2], MW[4]	BB[6] ***	x**	BB[11], BV[1]	
Investments for water level raise / water retention on agriculturally used peatlands		BB[6] ***, BV[7], LS[8] ***, MW[9]	x**	BB[11], SH[10]	BB[13], SH[13], MW[13]
Investment in harvesting machinery with low ground pressure and biomass processing technology		BB[6] ***	x**	BB[11]	

*Partly co-financed by federal states and/or nationally via German Joint Task for the improvement of agrarian structures and coast protection (GAK), **expected within the Natural Climate Action Program funding, ***expired, References: [1]StMELF (2024), [2]MLUK (2023a), [3]ML and MU (2023), [4]LM (2023), [5]MEKUN (2023), [6]MLUL (2016), [7]StMUV (2024), [8]NBank (2023), [9]EU Kommunal Kompass (2023), [10]Stiftung Naturschutz Schleswig-Holstein (2021), [11]MLUK (2023b), [12]NABU (2023), [13]www.moorfutures.de.

Next, to positive incentives via public funding, Isermeyer et al. (2019) consider an (initially national) emissions trading system suitable for initiating the rewetting of peatlands: the state includes all agriculturally used peatlands in the emissions trading system and landowners receive free emission rights for a certain period. They can either use them to maintain drainage or sell them (at a guaranteed minimum price) if they raise the water level. An ordinance needs to be established on how to proceed with individual land owners rejecting water levels from being raised, when the majority of land owners agree on rewetting. Including peatland emissions in an emissions trading system creates planning security and a long-term financing system for farmers. The land remains in private ownership and the owners/users decide on the type of (adapted) use, including paludiculture.

Other financing options emerge in Germany from different private or non-governmental initiatives, sometimes in close cooperation with public authorities. In the federal state of Schleswig-Holstein, so-called climate scores are derived by calculation of the CO_2 reduction potential from rewetting a specific drained peatland. These climate scores are paid by the federal state to the landowner, who only sells the rewetting rights (consent), but remains in ownership of the land. The remuneration is based on the calculated climate scores of the total area, the CO_2 price over a period of 35 years. The price for the climate scores will usually be higher than the purchase price on the land market (Stiftung Naturschutz Schleswig-Holstein, 2023). This approach is based on the MoorFutures, which are carbon certificates derived through peatland rewetting and sold on the voluntary market to refund rewetting costs (Joosten et al., 2015a). The same underlying GHG emission site type methodology to estimate emission reduction via a vegetation proxy (Couwenberg et al., 2011) is used for the NABU climate+ premium, where farmers get 65 € per reduced ton CO_2 per year for min. 3 (max. 10) years (NABU, 2023).

With the demand for renewable energy, the growth rates for ground-mounted photovoltaic (PV) on agricultural land are increasing (Böhm et al., 2022). Agriculturally used peatland can also be used for this purpose under certain conditions since the 2023 amendment of the Renewable Energies Act (EEG). The Federal Network Agency (2023) issued a decree specifying the requirements for special PV installations on grassland and on rewetted peat soils that have previously been drained and used for agricultural purposes. The construction of ground-mounted PV can take place on peat soils if these are permanently rewetted in connection with the construction. Due to the high rental income for land on which PV plants are built, farmers and landowners have high (income) expectations. Given this interest, PV on peatlands (with or without paludiculture) might provide an important lever for scaling-up rewetting. The practical and economic feasibility is currently under investigation.

5 Major fields of action

The large number of different approaches for overcoming obstacles to rewetting and paludiculture might be overwhelming. We suggest three major fields of action to avoid getting lost in options and ending up with no action. Since paludiculture is considered as an innovation mission (Ziegler, 2020; Ziegler et al., 2021), orientation can be provided by social innovation research that investigates how scaling innovation for systematic change is achieved in practice. Moore et al. (2015) identified three different types of "scaling" –scaling up, scaling out, and scaling deep – and concluded that large systems change requires the combination of all three types. "Scaling up" involves impacting laws and policies which we frame as "peatland mainstreaming" (section 5.1). "Scaling out" is about replication and dissemination of innovations. To support pioneers and motivate for a rapid transition in peatland management, a system of immediate and comprehensive incentives is needed (section 5.2). "Scaling deep" acknowledges that change must be deeply rooted in people, relationships and communities, e.g., through the reframing of stories and transformative learning. Empowering peatland communities to change cultural values, beliefs and practices is key to a just transition (section 5.3).

5.1 Peatland mainstreaming to adjust legal and policy framework

This review confirms the persistent lack of coherence of climate and agricultural policy as previously stated by, e.g., Regina et al. (2016), the European Court of Auditors (2021) and Chen et al. (2023). The dilemma however is much larger than the obvious wrong incentives set by the CAP. In fact, the specific characteristics as well as the potential of peatlands to contribute to climate mitigation and adaptation targets are still systemically neglected in the policy and legal framework. This common attitude, framed as the Cinderella Syndrome by Lindsay (1992), still holds true. While peatlands have a prominent role within the German Natural Climate Action Program (BMUV, 2023), were recently addressed in national peatland protection strategies (BLZV, 2021; BMU, 2021b) as well as in the proposal for an EU Nature Restoration Law (European Commission, 2022b), impediments to peatland restoration and paludiculture implementation are deeply manifested in the legal framework. This concerns regulations on soil, water, spatial planning, nature conservation, agriculture and forestry. On the one hand, the existing regulations do not distinguish between mineral and organic soils. On the other hand, former legislative procedures did not yet anticipate the challenges of the climate crisis.

This calls for "peatland mainstreaming" to acknowledge, strengthen and prioritize peatlands for climate change mitigation and adaptation. We derive the term peatland mainstreaming from climate mainstreaming, which is defined as "the integration of policies and measures to address climate change into ongoing sectoral and development planning and decision making" (Klein et al., 2005). We strongly emphasize both vertical (sectoral) and horizontal (intersectoral) peatland mainstreaming across all governance levels (*cf.* Rayner and Berkhout, 2012; Reckien et al., 2019). Peatland mainstreaming needs to focus on the sectors of agriculture and nature restoration within land use and land use change issues. The implementation of the proposed EU Nature Restoration Law (European Commission, 2022b) would provide a window of opportunity to determine more ambitious targets and specific steps for peatland restoration at the national level. Regional peatland strategies could facilitate the interaction of water, conservation and land use stakeholders, set clear and long-term transformation pathways, allow for planning security and offer regional balance of interests (Martinez et al., 2022). In addition, sectors related to paludiculture value chains, e.g., industry, energy and building sectors need to be integrated. Fundamentally, peatland mainstreaming entails the active alleviation of current impeding policies and regulations and the targeted introduction of supportive regulations (*cf.* section 4). Therefore, we extend the

mainstreaming definition used by Klein et al. (2005) from making use of "windows of opportunity" to actively redesigning the legal and policy framework in order to increase and accelerate rewetting.

5.2 Combining positive and negative incentives to motivate rapid transition

It is the fundamental premise of German peatland strategies that peatland rewetting takes place voluntarily. At the same time, ambitious climate mitigation targets and the high mitigation potential of peatlands are publicly communicated. This mismatch generates insecurity among peatland farmers. In consequence, a system of effective incentives is required to motivate farmers and landowners for a rapid transition. The effectiveness of financial incentives depends not only on sufficient financial resources, but landowners and farmers need to receive clear signals for planning security in the long term and a reasonable amount of time for adaptation of farm production processes and to convert to paludiculture (Schäfer et al., 2022).

Potential positive incentives for paludiculture are manifold and may address every step in the value chain. They can be applied directly to the land being rewetted; at the level of the farm that practices paludiculture and needs corresponding equipment; at the level of the processing company that develops, produces, and markets paludiculture commodities; and at the level of the product itself, whose properties have a positive effect on climate protection. In addition, accompanying measures can provide positive incentives for transition. As peatland boundaries do not correlate with property boundaries, new (faster) approaches are needed to establish mutual consent on rewetting and reorganize land holdings. One option to overcome this barrier are cooperative incentives linked with networking and consulting (*cf.* Van Dijk et al., 2015; Hirschelmann et al., 2020). Simplified and more flexible administrative arrangements to increase blended finance for peatland restoration are required (Moxey et al., 2021) to make full use of establishing positive incentives via European, national, regional funds as well as private financing.

In the medium term, negative incentives will very likely be introduced. The political principle of voluntary action means that rewetting will not be prescribed. However, keeping up drainage will become increasingly expensive for the single farmer and landowner. Internalizing social costs of carbon (damage costs) into production, e.g., via a carbon tax or a trading system for GHG emissions from peatland drainage (Isermeyer et al., 2019; Bognar et al., 2023) have been discussed. Certificate trading implements the polluter-pays principle, does not cause any fiscal financial needs, and could be highly accepted by land managers. Farmers should be given assistance with administrative procedures (Schäfer et al., 2022). According to the politically set targets, the number of emission certificates would decrease over time. This would bring CO_2 prices in line with actual abatement costs.

Therefore, we recommend a set of incentives to motivate for a rapid transition and provide clear guidance, with (a) positive incentives, which are immediate, attractive, comprehensive, and which start high but decrease until latest 2050 for fast voluntary rewetting, and (b) accompanied by gradually introduced negative incentives causing a time-lagged financial burden for rewetting deniers. Long-term announcement will set a clear course and provide planning security for farmers and landowners. Relying only on positive incentives while retaining the voluntary principle and existing drainage supporting regulations would lead to very high fiscal requirements and very likely not achieve large-scale peatland rewetting.

5.3 Empowering peatland rich regions to enable a just transition

Similarly to regions impacted by phasing out coal mining, the approach of "just transition" has been applied to peatland rich regions phasing out peat extraction, e.g., in Ireland (Banerjee and Schuitema, 2023) and Finland (Laasasenaho et al., 2022). To ensure that structural changes fit into the geographical realities, just transition policies need to include intangible local peatland assets by engaging people and communities living in, with and from the peatland in development processes (Banerjee and Schuitema, 2023). Beside this "procedural justice" it is also essential to include rural development into a long-term just transition policy plan (Banerjee and Schuitema, 2023), and to specifically include the local socio-economic and cultural fabric of peatland rich regions into rural development. For peatland regions dominated by agriculture, paludiculture provides an alternative to the abandonment of productive use, but public guidance and assistance in this transition is needed (Lehtonen et al., 2022). Besides, rewetting peatlands affects not only single farmers or landowners but also all local people, the self-perception and identity of communities as well as jobs and income generation along traditional value chains. By applying the principles of just transition not only to regions phasing out peat extraction but also to those stopping drainage of agriculturally used peatlands, the food (resp. paludiculture) processing and retail sector as well as consumers have to be incorporated as well (Lehtonen et al., 2022). Scaling deep by addressing hearts and minds of people is crucial for social innovation and new narratives (Moore et al., 2015). The importance of personal experiences and relationships and embodied learning are also highlighted for the perception of peatland restoration in Scotland (Byg et al., 2023). Engaging local stakeholders and communities in co-creation and co-governance ensures local ownership (European Commission e al., 2023). For the case of the Irish midlands, Flood et al. (2022) explored how rural communities and networks can transform social-ecological peatland resilience based on resistance (as agents of change), resourcefulness (capacity building) and rootedness (stewardship embedded in place). Empowering people and communities is a prerequisite to developing and pursuing perspectives tailored to their region. For this, a clear, honest communication on how climate targets translate into changes "on the ground" is urgently needed for farmers, land managers and communities to allow for long term planning and livelihood adaptation (Just Transition Commission, 2023).

6 Conclusion

Although the rewetting of drained peatlands has been identified as a key measure to contribute to climate mitigation, implementation falls far short of potential. Managed peatlands are complex systems, not only ecologically but also socially. A comprehensive research approach is therefore required. This policy and practice review provides a detailed overview of how land use decisions on peatlands are influenced by internal, i.e., farm and region specific, as well as external, overarching aspects. To our knowledge, it is the first extensive

mapping of the various aspects from the political, legal, economic and social dimension that hinder or enable the transition to sustainable peatland management from the local to the European level.

While we focus on the German case, the review can serve as a blueprint for investigating the situation in other European countries where peatland rewetting and paludiculture could also contribute significantly to meeting climate targets. As in Germany, drained agricultural peatlands contribute to more than 25% of total emissions from agriculture and agricultural land use in countries like the Baltic States, Finland, Sweden, Denmark, Poland, the Netherlands, the United Kingdom, Ireland, Romania and Austria (Martin and Couwenberg, 2021). In addition to some general or identical obstacles and approaches, country-specific needs have to be explored. For example, forestry and peat extraction are more important drivers of peatland drainage in the Baltic States and Finland than in Germany. At the same time, paludiculture as a productive alternative to abandonment after rewetting may be less important or feasible in countries with many remote peatlands where there is little or no industrial demand for renewable raw materials.

Any national-level investigation can be very valuable in providing a comprehensive overview but limited in identifying key drivers. Compiling a wide variety of experiences and solutions is not only overwhelming, – it blurs the diversity of peatland rich regions. Thus, more tailored analyzes for specific peatland regions are required. To better understand the social subsystem of peatland management, we need to expand research on region-specific challenges and opportunities (e.g., vegetable production on organic soils in Switzerland, Ferré et al., 2019) and analyze peatland management in specific regions as a social-ecological system (Ostrom, 2009) as applied for example by Buschmann et al. (2020) comparing six European peatland regions.

Despite all the differences and particularities, the major fields of action outlined in the previous chapter provide valuable guidance across regions and countries. Identifying region-specific drivers and deriving priorities for action within each of the three fields – peatland mainstreaming, clear incentives and empowering peatland communities – will contribute to achieving a just transition to sustainable peatland management.

Author contributions

SW: Conceptualization, Investigation, Visualization, Writing – original draft, Writing – review & editing. AN: Conceptualization, Investigation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2024.1380625/full#supplementary-material

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