Strategy and economic assessment of paludiculture for nutrient retention and other ecosystem services in the Neman River basin

Rewetted peatland Amalvas, Lithuania (Foto: Nerijus Zableckis)

Authors: Achim Schäfer and Wendelin Wichtmann
with the assistance of Michael Manton and Marina Abramchuk

Funding: This research was funded by the Interreg Baltic Sea Region project DESIRE (Development of sustainable (adaptive) peatland management by restoration and paludiculture for nutrient retention and other ecosystem services in the Neman River catchment) Index number R3071, project number #R091 implemented in the framework of the Interreg Baltic Sea Region Program, co-funded by the European Regional Development Fund.

Citation: Schäfer, A., Wichtmann, W. (2022): Strategy and economic assessment of paludiculture for nutrient retention and other ecosystem services in the Neman River basin. Greifswald University and Michael Succow foundation, partners in the Greifswald Mire Centre, Greifswald, Germany.

Inhaltsverzeichnis

UNIVERSITÄT GREIFSWALD Wissen lockt. Seit 1456 · Succow Stiftung · GREIFSWALD MIRE CENTRE · OGÓLNOPOLSKIE TOWARZYSTWO OCHRONY PTAKÓW · LIETUVOS GAMTOS FONDAS · Виштынецкий природный парк

0 Summary

Like many other river systems draining into the Baltic Sea, the Neman carries large amounts of nutrients into the Baltic Sea. This contribution could be noticeably reduced by rewetting peatlands throughout the river basin and converting their management to paludiculture. As a side effect, this could also avoid large amounts of greenhouse gas emissions. These positive effects of wetland buffer zones are well documented.

Implementation of paludiculture is connected with several advantages. There are many possibilities for the utilisation of biomass from paludiculture. Besides positive effects on biodiversity regular harvesting of the vegetation and export of the biomass from the area has an additional positive effect on nutrient reduction from the entire system. At the same time as the introduction of paludiculture, utilisation schemes for the sensible use of the biomass produced must be developed at the regional level as far as possible.

The four countries mainly contributing to the catchment area of the Neman River are considered by the Neman peatland database which was elaborated within the INTERREG project DESIRE (Manton et al. 2021). By this data base sufficient information is available on the basis of which top-down analyses can be made that allow a preselection of peatlands to be rewetted. The total available peatland area for rewetting and implementation of paludiculture can be estimated by considering the peatland areas that are affected by drainage and by that priority areas for restoration can be identified.

Costs and benefits of measures for hydrological restoration and implementation of paludiculture are outlined and discussed. Finally recommendations for the rewetting of peatlands in the whole river basin of the Neman River are given which may be used by responsible authorities and stakeholders as a basis for short term activities.

1 Introduction

1.1 Nutrient loads in the Neman River and eutrophication of water bodies

The Neman River (Nemunas, Memel) basin draining into the Baltic Sea through the Curonian Lagoon, which is the largest European estuarine lagoon under severe eutrophication pressure. Eutrophication is the increased availability of elements limiting primary production. The enrichment of the water body with nutrients, especially nitrogen and phosphorus compound, leads to an impairment of natural ecosystem functions. Anthropogenic nutrient inputs from the atmosphere, diffuse surface waters and groundwater inputs may lead to nutrient oversupply instead of nutrient limitation in many surface waters. This surplus leads to increased growth of algae and higher aquatic plants and to an undesirable impairment of the biological balance and quality of the water body concerned.

The Neman River transports large amounts of nutrients coming from different sources in the whole catchment area. The transboundary catchment area of 100,680 km^2 (Manton et al. 2021) is the fourth largest river basin that drains its waters into the Baltic Sea via the Curonian Lagoon. 47.7% of the basin in Lithuania, 46.4% in Belarus, 3.2% in Russia (Kaliningrad Oblast), 2.7% in Poland (Stachowicz et al. 2022), whereas 52% of the peatlands in the catchment area is in Belarus and 45% in Lithuania, the rest is in Poland and Kaliningrad area (Russia) (Manton et al. 2021).

Excessive nutrient inputs from river basins lead to eutrophication of adjacent water bodies and coastal waters and thus to undesirable changes in the functioning and structure of aquatic ecosystems. Between 2012 and 2016, the Neman River transported an average of 44,208 t of nitrogen and 1,547 t of phosphorus per year to the Curonian Lagoon (Vybernaite-Lubiene et al. 2018). Due to the high area shares, the largest pollution load from agricultural use in the Neman basin comes from Lithuania and Belarus. An estimated amount of 1,660 tonnes of phosphorus and 3,780 tonnes of nitrogen coming from transboundary waterborne pollution originating in Belarus (HELCOM 2008). Diffuse inputs from agricultural use in Lithuania account for 50% of total nitrogen and 33% of phosphorous and for 30% of total nitrogen and 37% of total phosphorous in Belarus (Nemunas river basin district management plan, 2017).

The Neman basin also contains organic soils that are drained and used for agriculture or exploited through peat extraction. As a result, peatlands degrade, and the nutrients contained in the soils (nitrate and phosphorus) are released into surrounding aquatic ecosystems. These issues can be mitigated by rewetting the peatlands and managing them in paludiculture[1]. Additionally wet peatlands reduce nutrients loads from waters feeding them.

1.2 Strategy and economic assessment

The rewetting of several thousand hectares of peatlands in the Neman basin cannot be accomplished overnight, but requires a long-term strategy in which, in addition to time, effective mitigation concepts must be identified and developed in a participatory dialogue or in a top-down, command and control process. This process must be intensified on national level, supported by international cooperation of all countries contributing to nutrient export from the Neman River basin.

Meeting the challenges in land use change requires a long-term plan that defines precisely how the overarching goals of water, climate and biodiversity protection policies can be achieved with sustainable peatland use. In the strategy presented here, criteria for the necessity of measures are formulated to describe the land potential and site-specific conditions for nutrient retention through the rewetting of peatlands and conversion to paludiculture.

[1] Paludiculture is crop cultivation on wet peatlands (Wichtmann et al. 2016).

The various components of the strategy serve as a basis for public and private sector decision-makers to weigh up rewetting and conversion to paludiculture in the Neman catchment. In this decision-making process, numerous scientific, socio-economic, and political factors must be considered regarding the impacts of measures to prevent water pollution. Against this background, the conceptual and methodological framework of the strategy focuses on quantitative analyses of land use options that have an impact on water quality and are intended to contribute to water protection on productive agriculture land.

The strategy facilitates a cross-disciplinary process of understanding and provides relevant background knowledge for private and political decision-makers as well as concrete approaches to solutions for nutrient retention by land use change in peatlands. The development of a strategy should take place in the role of an impartial observer and show the private and political decision-makers target-oriented ways for specific issues. In this sense, the strategy makes clear in which peatland areas nutrient retention is a priority, where nature conservation objectives must be considered or are more important.

The identification of land potentials for nutrient retention through rewetting of peatlands and conversion to paludiculture must be based on environmental policy targets. This leads to an overlapping of water and climate protection policy targets regarding societal requirements for future peatland management. According to the Paris Agreement, all drained peatlands in the Neman River basin must be rewetted by 2050 from a climate protection perspective. Within this framework, a theoretically possible transformation pathway can be used to quantify the land required for rewetting and the potential for conversion to paludiculture for climate and water protection.

From an economic point of view, the question arises as to which instruments can be used to achieve the politically defined goals. In addition, for targeted economic instruments (e.g., tenders for participation in agri-environmental programs or payments for ecosystem services), information is needed to assess the cost-effectiveness of the measures. For a comprehensive economic assessment of cost-effective measures of rewetting and conversion to paludiculture, information is needed that is only rudimentarily known. This applies above all to the conversion to paludiculture, which is associated with very high initial investments and is only implemented in practice in a few scientific pilot projects. Consequently, the demand for paludi-biomass and the further processing into paludi-products is so far only rudimentary in niche markets.

2 Peatland restoration for nutrient retention

2.1 Peatlands, nutrients, and carbon

Water saturated peatlands play a role as sinks for nutrients, pollutants, and carbon in the landscape. If peatlands are drained to be used for agriculture or forestry, or to extract peat, they go from being a sink to a source. As a result, the nutrients in the soils (nitrate and phosphorus) are released and pollute surrounding aquatic ecosystems and climate impacting greenhouse gases (GHG) are emitted into the atmosphere. This means that all degrading peatlands in the Neman River basin contribute to climate change and to eutrophication of the river and pollution of the Baltic Sea.

In addition to the GHG emissions, nutrient emissions from drained peatlands must be considered from a water protection perspective. Draining peatlands causes the discharge of nutrients via drainage water. By this, large amounts of nitrogen and phosphorus are released to surface waters. This means that drainage and intensive, large scale agricultural use of peatlands lead to the impairment of important ecological functions and negative external effects that can extend far beyond the peatland area. Mineralization of drained organic soils and excess use of fertilizers lead to pollution of adjacent surface waters (rivers, lakes), groundwater, and seas with nutrients. Consequently, surface waters suffer from cyanobacteria blooming, formation of micro- and macroalgae mats and oxygen deficiency. As a result, living conditions for fish and other aquatic organisms are deteriorated, which has also negative impacts on aquatic biodiversity, as well as on fishery, tourism industries, and local people's livelihoods.

Intact and successfully restored peatlands serve as “kidneys of the landscape” by filtering nutrients from ground- and surface water that flows through them. Moreover, wet, and rewetted peatlands may retain nutrients which they receive from their feeding waters and natural deposits. Under waterlogged soil conditions these nutrients may be taken up by the growing vegetation, eliminated (like Nitrates which volatilised after denitrification as N_2) or precipitated (like Phosphorus) and on the long run be sequestered by transforming plant biomass into newly formed peat (Vroom et al. 2018). The removal of nutrients by harvesting paludi-biomass from rewetted peatlands has additional positive effects on water protection (Geurts et al. 2020). Studies in fens (ground- and surface-water-fed peatlands) in the Netherlands involving biomass harvest showed nitrogen retention efficiencies of up to 93–99% (Koerselmann 1989, Wassen & Olde Venterink 2009).

Furthermore, peatlands can accumulate nutrients and carbon by transforming plant biomass into peat under waterlogged soil conditions. In addition to the reduction of soil borne GHG emissions through rewetting, other positive climate effects are associated with the conversion to paludiculture: (a) by fixing carbon in the product (for durable products such as construction and insulation materials, furniture, and moulded parts) and (b) by substituting fossil fuels and raw materials (e.g., for heat generation, insulation materials, packaging) for a limited period until 2050.

2.2 Peatlands and interactions with societal requirements

The rewetting of peatlands and the conversion to paludiculture does not take place in a vacuum but must take place against the background of the currently existing institutional, legal-administrative, and interest-political governance structures. According to the Paris Agreement, the increase in global average temperature should be kept well below 2 °C and efforts should be made to limit the increase to 1.5 °C above pre-industrial levels (UNFCCC 2015). In line with this scientific based 1.5°C target, all sectors must contribute to GHG mitigation. This also affects the land sector, where measures need to be implemented in agriculture and forestry (IPCC 2019). Limiting global warming to 1.5 °C means reducing net global carbon dioxide (CO_2) emissions from anthropogenic activities to zero by 2050 (IPCC 2018). This means for peatlands, that almost all must be rewetted by 2050 at the latest.

Rewetting, which is necessary from a climate protection policy point of view, can also help to achieve water protection policy objectives. While the rewetting of peatlands is sufficient for GHG emissions reduction and the skimming of biomass is not crucial, targeted wetland management with skimming and further processing of the biomass makes sense from both points of view, the carbon sequestration, and the water protection policy.

The existing water protection policy objectives shall achieve Good Ecological Status of rivers and thus contributing to achievement of the Good Environmental Status of the Baltic Sea in the European riparian states. According to the updated Baltic Sea Action Plan adopted from the contracting HELCOM countries (including Russia but without Belarus) these regulations should contribute towards for the reduction of excessive nutrient levels.

The legal framework associated with water resources and related issues in the European Union (EU) is the EU Water Framework Directive (WFD), to which all the EU member countries must comply. The WFD requires member states to achieve a good ecological status of water bodies by 2027 (European Parliament and European Council, 2000). The WFD adopted in 2000, takes a pioneering approach to protect water based on natural geographical formations: river basins. An important concept considered by the WFD is the river basin approach as the best way to manage water resources. Neman River Basin is subject to WFD, whereas HELCOM is the governing body of the Convention on the Protection of the Marine Environment of the Baltic Sea Area, which Lithuania, Latvia, Poland, Russia, as well as other riparian counties of the Baltic, are members of. Belarus takes part as an observer to the Convention on the Protection of the Marine Environment of the Baltic Sea Area but not must to fulfil commitments the Convention.

Against the background of the high proportion of organic soils and nutrient loads from Belarus mentioned above, the latter aspect is important for deriving measures and recommendations for nutrient retention through rewetting of organic soils and conversion to paludiculture. In the Neman basin, there are also different structures of environmental policy and concepts for resource management and the use of economic policy steering instruments. In contrast to the inclusive and adaptive governance structures of the Aarhus Convention (e.g., transparency, participation, equity, deliberation, and legitimacy), Belarus has strong top-down command control in the environmental sector, including state ownership of all land and natural resources.

The objectives in the above-mentioned environmental policy areas of peatland use partly overlap and can only be considered with difficulty in isolation, because land use change can be associated not only with synergies but also with conflicting objectives. Due to the potentially high significance of nature conservation, possible impacts on the biodiversity typical of the peatlands must also be considered during restoration. It should be noted that the drained sites, which are the focus of water protection by hydrological restoration, are generally not of high nature conservation importance because they are deeply drained and intensively used for agriculture, and they are currently often abandoned in the Neman iver basin. In individual cases, expected negative impacts of a land use change on biodiversity can be avoided on an area-specific basis with existing planning instruments.

The achievement of the various environmental policy objectives must also be considered in the economic analysis of target-oriented measures and instruments. Private-sector interests, social improvements and environmental protection goals often seem difficult to reconcile at first glance. Strategies for sustainability attempt to bring together precisely these interests. For the use of peatlands, this means that the numerous, very different multifunctional social demands must be continuously reconciled. However, insofar as societal welfare is indispensably based on ecosystem services, long-term environmental compatibility must be given priority over short-term economic or social benefits.

Rewetting organic soils and conversion to paludiculture are an integral part of restoration of a green infrastructure strategy (Estrequil et al. 2019) that can support the WFD and HELCOM goals and provide numerous ecosystem services that are relevant to the welfare. The rewetting of the peatlands improves water quality in the Neman basin by retaining nutrient loads from agricultural use in the catchment area. The rewetted peatlands act as a nutrient sink. These can also be used for agricultural purposes. For this, however, the conventional drainage-based use must be converted to wet production methods. The ability of rewetted peatlands to retain nutrients is enhanced by paludiculture, as harvesting nutrient-rich biomass from rewetted peatlands removes nutrients from the sites.

After rewetting, it is largely no longer possible to continue conventional agricultural use. However, with a conversion to paludiculture, the land can be kept in production and nutrients retained by harvesting the biomass. However, paludiculture offers the possibility to continue using peatlands for agriculture and forestry after the water level has been raised, thus contributing to a sustainable circular economy (Tanneberger et al. 2020a). For this, the conventional drainage-based agricultural use of peatlands must be converted to wet peatland management (paludiculture).

Such an approach is a paradigm shift in peatland management, the implementation of which is associated with numerous obstacles and practical challenges (water management, lack of experience). In addition, there is a lack of incentives for the conversion of agricultural production methods and the utilisation of paludiculture biomass to be developed in parallel, as well as a (still) non-existent demand for paludiculture products.

3. Effects of rewetting of peatlands and conversion to paludiculture

3.1 Effects on nutrient balance

The **drainage and agricultural use** of peatlands -as well in the Neman catchment area - leads to soil degradation and destruction (deterioration, mineralization, compaction, subsidence, erosion, devastation), GHG-emissions and water pollution by nutrient release. Peatlands can also deteriorate due to other causes coming "from outside" the catchment, e.g., pollution and nutrient enrichment (e.g. deposition, upstream fertiliser run-off from agriculture). The latter is clear in the case of pollution or nutrient-enrichment by incoming surface- or groundwater.

There are several biogeochemical processes which relate to **rewetting of peatlands** and conversion to paludiculture which may have an influence on nutrients retention and potential resolution. Various studies show that the physical properties of the most disturbed near-surface peat soils do not correspond to the reference conditions of a near-natural peatland even several decades after restoration, although the natural water table has been restored (Kreyling et al. 2021). While restoration methods have improved in recent years, restoring natural hydrological conditions still cannot be considered a simple process where success can be guaranteed. Several studies have shown that the most serious problem for water protection can be the increased leaching of phosphorus from rewetted sites which were drained and fertilized in the past and have an unfavourable iron-phosphorus ratio (Land et al. 2016, Zak et al. 2014, Audet et al. 2020, Negassa et al. 2020, Walton et al. 2020b).

Different **effects of rewetting on biogeochemical processes** can be observed. By rewetting all pores of the peat soil are filled with water, air is displaced, oxygen is no longer present or only present to a small extent. Strong changes in the Redox system take place. By this the conditions for denitrification of nitrate are improved, ammonium is resolved, and phosphorus compounds previously considered very stable may go into solution (Lundin et al. 2017). Such a change from oxic to anoxic conditions on one hand can ensure that 100 % of the nitrate nitrogen is reduced to N_2 without causing damage. On the other hand, this can lead to a reductive dissolution of iron III compounds and consequently to the release of phosphates. This is especially relevant in fertilized grasslands and arable lands on peat, which are enriched with – under drained conditions – unsoluble phosphate-complexes. This process can lead to very high P concentrations in the pore water (Gelbrecht & Koppisch 2001) and can be very extensive if the ratio of iron to phosphorus in the topsoil of the peatland to be rewetted is less than 10 (Jabłońska et al. 2020). The redissolved phosphorus can be (partially) absorbed by the vegetation and exported with the harvest from the area, but it can also be discharged with the water, especially in flow-through (respectively percolating) rewetted peatlands and may contribute to pollute the water bodies. This means that there is a risk that phosphorus accumulated in peat soils will be released downstream (Audet et al. 2020).

The presence of a site adapted peatland typical **hydrology** is crucial to achieve the goals of peatland soil protection and the reduction of nutrient losses. It is difficult to restore natural hydrological conditions in peatlands that have undergone major changes since they were drained and have therefore lost their original vegetation and the natural structural features of the peat layers at the surface. Such peatlands were often naturally nutrient-rich sites with abundant water flow. Hydrological conditions can be restored in the long term if peat-forming plant species are established and vice versa (Rehell et al. 2014).

Although the methods for restoring ecosystem functions of drained peatlands are still limited and hardly tested, initial recommendations can be made. If the peatland has been recently weakly drained and the hydraulic properties have not changed irreversibly, restoration measures can be limited to rendering the drainage infrastructure ineffective (Pfadenhauer & Grootjans 1999, Menberu et al. 2018, Klimkowska et al. 2020). Peatlands with significant hydraulic changes and long-term drainage are characterised by a decrease in peat porosity, hydraulic conductivity, and storage capacity. The associated changes in the hydraulic properties of the peat are largely irreversible in these peatlands (Carroll et al. 2011, Chimmer et al. 2017). To improve nutrient retention, water levels, water dynamics and water quality in the peatland itself and in the catchment must be considered (Sallantaus 2014). Since the extent of irreversibly disturbed hydraulic properties in the catchment area of the Neman is not known, this information should be collected in the context of hydrological planning.

Against the background of limited scientific evidence, it is difficult to **quantify the ecosystem function for nutrient retention** ex-ante. Specific improvements in nutrient retention through a particular restoration measure can only be quantified once all effects have become clear. It should be noted that in the short term, nutrients may be washed out from restored peatlands, but the quality of runoff from the peatlands improves in the longer term after restoration. If the goal is to restore the natural hydrological processes in a peatland, then active measures are required. Apart from doing nothing, there are two main options for restoring the ecosystem function of nutrient retention:

- remove the extremely nutrient-rich top layer before rewetting (Zak et al. 2016)
- remove nutrients by harvesting the biomass after rewetting (paludiculture).

The first option is practised in terms of area for nature conservation reasons in small-scale restoration of sensitive plant communities. Since extremely large amounts of "soil" must be moved and this causes very high costs, this option does not appear to be very effective as a measure for nutrient retention. Furthermore, it must be considered that the problems are spatially displaced if there is no reasonable use for the nutrient-rich sward. Due to the marginal relevance of the area, the removal of topsoil for nutrient retention is to be assessed as insignificant.

Several **factors are determining the amount of nutrient loads** from peatlands to ground and surface waters. They depend e.g. on peatland type, drainage- and land use intensity. As a majority of peatlands are fens, a substantial part of the agriculturally used peatlands in the Neman catchment area is rather nutrient rich (see table 2: Peatland types in the Neman River basin). The highest nutrient discharges are to be expected in arable farming (as driving over with heavy equipment is only feasible at lower water levels and there is no "supporting" sward and fertilizer input is assumed to be higher than on grasslands). Lower, but still significant nutrient release is estimated for semi-natural grassland and meadows. Therefore, nutrient retention can most effectively be achieved by rewetting deeply drained peat soils and converting to nutrient-skimming paludiculture. From a water protection policy perspective, it should be considered that not only drainage-based agricultural use is associated with nutrient inputs into adjacent aquatic ecosystems, but also the abandonment of agricultural use. In Belarus, for example, almost half of the peatlands are abandoned areas that function as nutrient sources with a disturbed hydrological regime (Bambalov et al. 2017). For the conversion of drainage-based peatland use to paludiculture and its contribution to nutrient retention in the catchment area of the Neman River, the question of the current agricultural use of the peatlands also arises from an economic perspective.

3.2 Wetland buffer zones

A 'wetland buffer zone' (WBZ) is the transitional riparian area between terrestrial (e.g., agricultural land) and aquatic environments. WBZs purify waters by removal or retention of nutrients present in waters moving from terrestrial to riverine ecosystems, for instance, from agricultural fields to rivers. The projects DESIRE and CLEARANCE have reviewed 82 studies from 51 publications on the removal efficiency of nitrogen (N) and phosphorus (P) by wetland buffer zones in temperate regions (Northern and Central Europe, Northern USA; Walton et al. 2020). Various types of wetland buffer zones were included in the review: e.g., fens (ground- and surface-water fed peatlands), and floodplains with mineral soils "- wetlands" along streams or rivers. Wetland buffer zones may significantly improve water quality by filtering out agricultural nutrients such as nitrogen (N) and phosphorus (P).

Walton et al. (2020) could show that WBZs work as effective barriers for diffuse nutrient pollution from agriculture and ought to be recognized in large-scale, long-term pollution management. The biological, chemical, and physical processes allow a WBZ to act as a nutrient sink. But Walton et al. also determined that mineralizing and degrading peatlands release large amounts of mobile dissolved N and soluble reactive phosphorus. They compared WBZs with organic soils (peatlands) and mineral soils and found similar nitrate retention efficiencies (53±28%; mean ± sd and 50%±32). After Walton et al. 2020 the mean removal efficiency of both organic and mineral soils is 80% for total nitrogen (TN) and 70% for nitrate (at a load of < 160 kg N*ha*year). Higher loads of nitrogen in the catchment area (> 160 kg N*ha*year) reduce TN removal efficiency of WBZs from 80 to 31 %, thus restoration of WBZs must be integrated with reduction of nutrient inputs from the catchment area, whereas Vroom et al. (2022) could show that increased nitrogen in inflowing waters can improve the uptake of other nutrients and leads to higher yields of cattail. Also, Trehan et al. (2022) could show by an empirical model, that in addition to avoiding nutrient input through fertilisation of arable and grassland areas and reducing the mineralisation of peat in peatlands through rewetting, the retention and elimination of nutrients in rewetted peatlands, which are established as WBZs, is an important measure for reduction of environmental burden.

The longer water resides within a WBZ, the more efficient nutrient removal and retention are (Walton et al. 2020). Vegetated land is generally more efficient in nutrient retention than bare soil, but nutrients are remobilized by decomposition of biomass material after the plants die off. Trees store nutrients reliably and long-term, but they grow slower than herbs and grasses. Forest age also affects nutrient uptake: young trees have a higher nutrient requirement. Mowing and removal of plant biomass from a wetland can remove nutrients from the WBZs. Ultimately, they state that large-scale WBZ restoration is necessary to improve water quality and meet WFD requirements.

Overall, WBZs can efficiently remove nutrients from water flowing to surface- and groundwaters, thus helping to maintain a better water quality. However, many factors determine their nutrient removal efficiency, for instance, hydrology, soil characteristics, vegetation cover, nutrient input, and agricultural use. Thus, restoration of peatlands in general needs to be assessed individually to evaluate its potential for nutrient removal, as it reduces losses from mineralization in peatlands and purifies ground- and surface waters from the catchment. The contribution of peatlands to nitrogen loss can be assumed as the sum of N loss from the agriculture activity and the nitrogen loss being generated because of the mineralization of peatlands (Holden et al. 2004). Retention efficiency of WBZs depends on the incoming loads and is inversely proportional to the N loads (Walton et al. 2020).

3.3 Plants for paludiculture

The most up-to-date knowledge on paludiculture plants suitable for the catchment of the Neman River was compiled corresponding to Tanneberger et al. 2020. Plants with a good potential to become established on rewetted peatlands are common reed (*Phragmites australis*), sedges (*Carex* spp.), cattails (*Typha* spp.), reed canary grass (*Phalaris arundinacea*), and black alder (*Alnus glutinosa*) (Abel et al. 2013) also, animals such as Water Buffalo (*Bubalus bubalis*) can graze on wet peatlands dominated by reedbeds and sedges. The climatic conditions in the catchment area partly also favours the cultivation of peat moss (*Sphagnum* spp.), Sundew (*Drosera* spp.), Cranberries (*Vaccinium oxycoccus*) or Cotton grass (*Eriophorum* spec.). Practical knowledge for some types of paludiculture exist at minor scale, e.g. harvesting Common Reed for thatching (Wichmann & Köbbing 2015, Wichmann 2017), sedges/grasses for combustion, Alder for timber (both described in Wichtmann et al. 2016) and keeping Water Buffalos (Sweers et al. 2014. For other species such as cattails, knowledge from pilot sites exists (Oehmke & Abel 2016; Geurts et al. 2019), but field-scale implementation is just starting, e.g. in the Netherlands and in Germany and there is still uncertainty on practical farming aspects, biomass quality and profitability (Schröder et al. 2015). An overview of the broad spectrum of potential paludiculture plants is provided by the database of paludiculture plants (DPPP), which is regularly updated and available to the public on the homepage of the Greifswald Mire Centre.

3.4 Utilisation of biomass from paludiculture

The portfolio of high-quality utilisation options is very versatile and partly still unknown. The wide range of plant species offer diverse potential for different applications in industry and crafts, energy, agriculture and beyond. Products made from paludi biomass have additional positive properties compared to products based on fossil raw materials. Paludiculture plants have adapted to their wet habitat with special properties. Cattail leaves, for example, have an aerial tissue that gives the leaves and products a very high stability despite their low weight. Other plant species store silicates that are fire- and fungus-retardant in the product. Peat moss has a very high-water absorption and water storage capacity as well as antimicrobial properties and can replace fossil peat as a raw material for horticultural growing media. It can also be used as a raw material to produce bandages and nappies and as packaging material.

3.4.1 Use in agriculture

There are many traditional and new ways to utilize paludi-biomass in agriculture. In addition to utilization of various grasses as fodder (especially if early harvesting dates are possible), utilization as bedding materials for lifestock and composts as fertiliser and substrates for horticulture is also possible. The biomass can be composted or the residues after biogas fermentation and ashes from direct combustion can be used as a fertilizer.

3.4.2 Energy use

The paludi-biomass can be used e.g., as fuel, as substrate for biogas production or to produce liquid energy carriers. Many plant species are suitable for energetic utilization, whether as a single-variety material or as a mixture of different plant species. However, it seems important that the composition and quality of the biomass should be permanently consistent, e.g., for combustion. Productive wetland species such as reeds, sedges, bulrushes, and cattail grass are eligible. The biomass from one hectare of common reed (winter yield = 8 t DM) used for combustion equates to an energy content of about 3,000 liters heating oil. Besides utilization in biogas plants (Martens et al. 2021, Czubaszek et al. 2021), thermal utilization in heating (power) plants is the most important option. A district heating plant (800 kilowatt) in northeast Germany demonstrates the feasibility of using biomass from wet fen meadows for local heat generation (Wenzel at al. 2022). Moreover, tests of biomass pellets from paludiculture showed promising results for small (< 100 kilowatt) and medium scale boilers (< 500 kilowatt) (Dahms et al. 2017).

Combustibility differs between plant species as well as between harvest dates. Generally, biomass harvested in late autumn or winter contains less critical elements for combustion, e.g., Chlorine, Potassium and Nitrogen. At the same time, the yield and possible nutrient export from the peatland site will be reduced (see section 4).

For energetic use unspecific biomass on large scale can be harvested from wet peatlands after rewetting and establishment of productive vegetation. The biomass quality (contents of nutrients) plays some role which may be influenced by date of harvesting (early: biogas, late combustion). Early harvesting can extract significantly more nutrients than late harvesting. To this end, the existing technologies for utilization of biomass must be adapted (e.g., heating- and biogas-plants).

However, the land potential is limited, although the demand for energy is currently many times higher than the supply. A limiting factor in energy recovery is the very limited transportability of paludi-biomass and the complex and cost-intensive refinement processes. Nevertheless, under certain conditions (e.g., existing infrastructure), energy recovery can be a sensible alternative for decentralised energy supply.

3.4.3 Material use in industry and handicraft

In contrast, the material utilisation of biomass appears to be more suitable. The limited transportability does not have to be a disadvantage. Regional processing into intermediate and end products is possible where the biomass is produced. In this way, value creation can take place in structurally weak rural areas and contribute to the environmentally friendly transformation and development of rural areas.

Also, paper, fibres, packaging materials and mouldings are interesting options for the utilization of specific paludi-biomasses. The quality demands for the biomass for most of these uses are high homogeneity and low humidity. The material options for biomass utilisation in general demand for specific, high-quality biomass and the non-existing processing capacity is a limiting factor. In the long term, material utilisation has high value-added potential and should be implemented with the expansion of processing capacities. Other types of paludiculture are currently tested: Growing of Sphagnum mosses on rewetted bogs might substitute peat in horticulture and grazing with water buffalos can be a sustainable way to produce meat and dairy products in wetlands. In this way, paludiculture could be a win-win-situation of restoring degraded peatlands and continuing to use the land in an environmentally friendly manner. Harvesting of biomass helps to remove nutrients (including agricultural pollutants) from rewetted peatlands, which prevents them from being discharged into surface- and groundwaters.

3.5 Effect of harvesting on nutrient retention

At a rewetted fen peatland research site in Poland, the total N removal reached 34 – 92 % and total P removal 17 – 63%. N removal was directly related to the initial N concentration, regardless of mowing status. A high N removal efficiency (92 %) was found in the harvested site. Mowing and dead biomass removal might be therefore a prominent mechanism of P removal in rewetted peatlands. P uptake by wetland vegetation during the growing season mitigates the high P mobilisation in rewetted peat (Zak et al., 2014), but a large part of the P in the aboveground biomass will be released after dieback of plants through leaching and subsequent decomposition if the vegetation is not mown and removed. Depending on harvesting dates and specific site conditions investigations on rewetted not fertilised peatland sites in Mecklenburg harvesting of biomass resulted in export of 44 – 133 kg N, 3,4 – 14,4 kg P and 5,7 – 50,7 kg K per hectare (Wenzel et al. 2022).

With an online tool based on a literature data base the potential amount of nutrients which can be exported from a rewetted fen peatland can be assessed (Oehmke, unpublished). Different site conditions, dominating plant species and harvesting times can be considered. Figure 1 and Table 1 exemplarily show the results for an organic site dominated by Common Reed which is harvested in summer, autumn, and winter season. The results show how many nutrients are removed from the system which are no longer available for leaching into groundwater or surface waters.

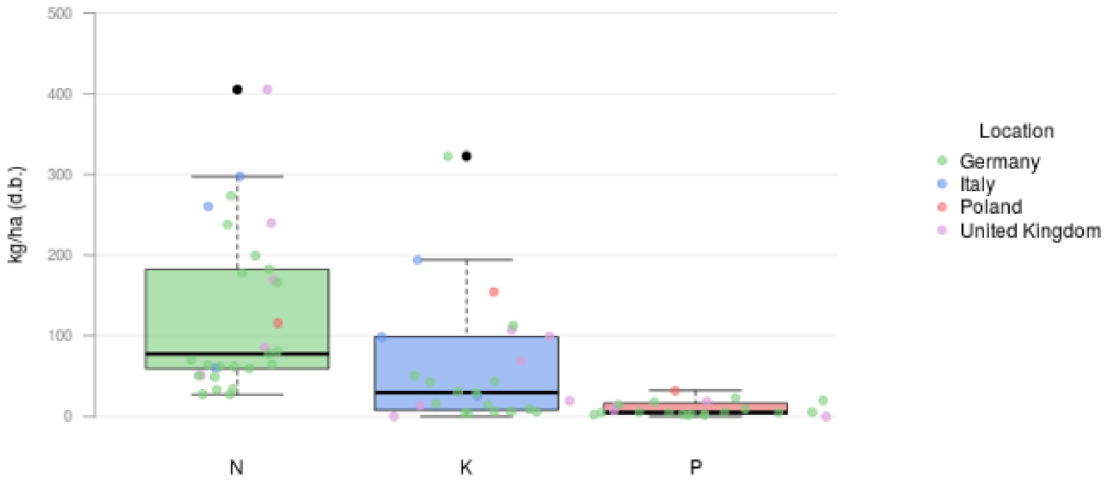

Figure 1: total N and total P removal potential by harvesting biomass from a medium well nourished reed stand, based on a literature review from Germany, Poland, Italy, and UK

On rewetted peatland sites which are not regularly harvested these large amounts of nutrients are exposed to the risk of leaching. By optimising the date of harvesting, and considering the dominant plant species, maximum export rates can be achieved for the individual nutrients.

Table 1: Removal potential of total N, K and P (kg/ha) by harvesting reed biomass, assessed with the CLEARANCE online tool based on a literature review from Germany, Poland, Italy, and UK

	N	K	P
Min	27.49	0.02	0.02
Median	77.67	29.86	5.27
Mean	127.15	60.88	9.61
Max	405.50	322.83	32.10

4 Results - Land requirements for rewetting and potentials for conversion to paludiculture in the Neman River basin area

4.1 Analysis of the data base

The rewetting of peatlands is the only way to reduce soil borne GHG and nutrient emissions from drained peatlands (and other organic soils). It is not necessarily linked to the establishment of paludiculture. Land use changes and peatland areas suitable for rewetting are required to achieve the specified climate and water protection policy goals. The land requirement is determined based on current literature (Manton et al. 2021) and under the premise of a hypothetical future consideration in the sense of a scenario analysis. This should assume that the required areas are available for restoration and that rewetting can be carried out in accordance with the environmental protection policy targets.

4.1.1 Peatland area

Peatlands are areas with a naturally accumulated peat layer at the surface (thickness not defined, but in most countries minimum 30 cm) and peat is material accumulated in situ which consists at least 30% of dead organic material; organic soils have a substantial layer of organic matter at or near the soil surface (Joosten et al. 2017). There is a large diversity of peatland types in the Neman basin which in the following are summarized as fens, transitional mires and raised bogs (table 2). Fens are peatlands that receive water that has been in contact with mineral soil or bedrock (e.g., groundwater, inundation with surface waters), a bog is a mire only fed by precipitation, and transitional mires show properties between a rich fen and a raised bog (Joosten et al. 2017). Referring to the Neman peatland database the Neman River basin consists of 1,006,802 ha (table 2) of peatlands, with Belarus having the largest share (52%), followed closely by Lithuania (45%), while both the Polish and Russian parts of the Neman River basin contain only relatively small proportions of peatlands 2% and <1%, respectively. The area of fens in the Neman basin covers 764,005 ha (75,9%), the transitional mires and raised bogs amount to 116,509 (11,6 %) and raised bogs 126,288 ha (12,5 %).

Table 2: Peatland types in the Neman River basin

Peatland-type	area (ha)	%
Fen	764,005	75,9
Transitional mire	116,509	11,6
Raised bog	126,288	12,5
Total	**1,006,802**	

Table 3: Land use on peatlands in the Neman River basin

Land use	area (ha)	%
Agricultural land	173,768	17.3
Forest	357,530	35.5
Natural peatlands	70,580	7.0
Other	2049	0.2
Pastures and meadows	260,779	25.9
Quarry	115,000	11.4
Semi-natural grasslands	16,277	1.6
Urban	184	0,0
Water bodies	10,636	1.1
Total	**1,006,802**	

Natural peatlands are 7% of the total (Tab 3), more than 11 % are designated for peat excavation (115,000 ha). 2156 ha of these “quarry”-peatlands show no impacts by drainage (table 6). This seem to be the “reserve” sites for peat excavation. 26% are used as pastures and meadows and 17 % are used as agricultural (arable) lands which per se is the land use form which contributes strongly to GHG and nutrients emissions.

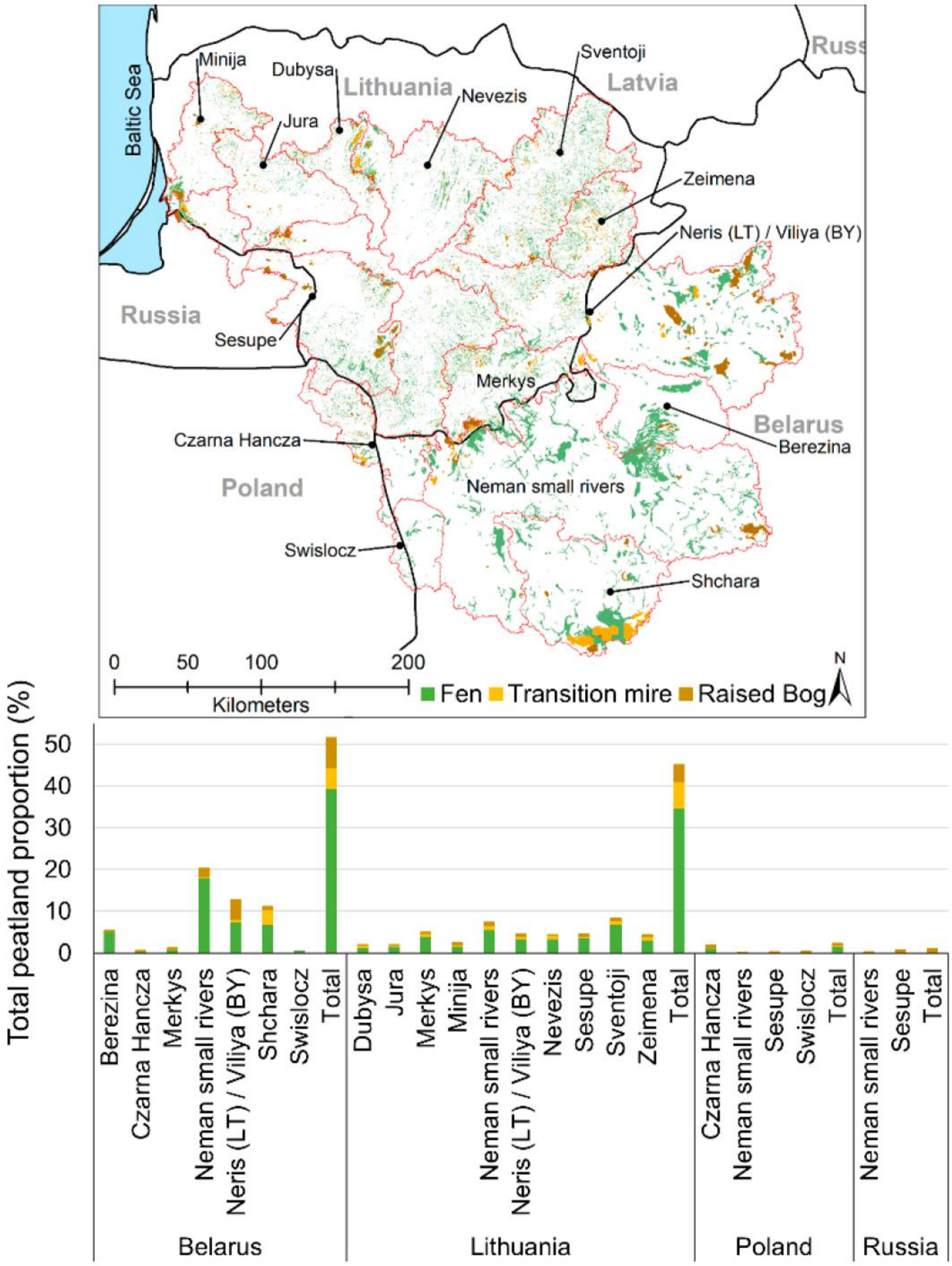

Figure 2: Map of peatlands and their area proportions within the entire Neman River basin by country, sub-basin, and peatland type (fen, transitional mire, and raised bog; Manton et al. 2021).

Differences between peatland types must be considered. Table 2 and 4 show that fen peatlands in the whole Neman River basin account for the largest share. This may be interesting for rewetting potential (easier to rewet are large areas in fens) and higher potential for nutrients retention, as fens in most cases are more nutrient rich than transition mires and bogs, and – additionally to reduction of mineralisation of peat in the peatland itself – also in fens polluted „input“ water can be treated (act as WBZ). This is in general not possible in bogs.

The lower part of figure 2 shows the proportion of peatlands in the catchment areas of respective countries (Manton et al. 2021), see also table 4 with Belarus (especially in the ‘Neman small rivers’ sub catchment) and Lithuania providing large fen areas (table 4). This means that measures of re-wetting and implementation of paludiculture aiming at nutrients release from the aquatic ecosystems must predominantly be taken in fen peatlands within these two countries so that effective nutrient reduction in the river can take place.

Table 4: Peatland distribution in the Neman River basin by country and peatland type (area ha)

Country	Fen	Transitional mire	Raised bog	Total
Belarus	396,782	48,963	73,931	**519,676**
Lithuania	349,056	64,202	40,731	**453,990**
Poland	16,366	3,163	3,738	**23,267**
Russia	1,801	181	7,888	**9,869**
Total				**1,006,802**

Source: Peatlands of Neman basin. Pivot excel sheet from MM 14.1.22

4.1.2 Protection status of peatlands in Neman basin

About a quarter of all peatlands in the Neman River basin are somehow protected areas and are only available for conversion to paludiculture to a limited extent (table 5). Most of them are forests (154,627 ha), pastures and meadows (41,049 ha) and natural peatlands 37,640 ha). The nature conservation laws and data bases which are available for the whole catchment area may exclude a change of those nowadays existing ecosystems, which may be summarized under “protected areas”, nature reserves, national parks, legally protected biotopes, natural monuments, or habitat types of the FFH directive. The Neman peatlands database does not allow further distinguishing. Manton et al. (2021) point out that the management objectives and measures can vary widely, from strict protection without interventions to protected areas with management interventions.

Table 5: Land use on peatlands in the Neman River basin and protection status

Land use	Protection status		Total area (ha)
	Not protected	Protected	
Agricultural land	164,695	9,073	**173,768**
Pastures and meadows	219,730	41,049	**260,779**
Forest	202,903	154,627	**357,530**
Quarry	101,629	13,371	**115,000**
Natural peatlands	32,932	37,648	**70,580**
Semi-natural grasslands	10,649	5,628	**16,277**
Water bodies	7,117	3,520	**10,636**
Other	1,626	423	**2,049**
Urban	184	0	**184**
Total	**741,465**	**265,339**	**1,006,802**

In the Neman River basin, there are different categories of protected areas, which are extremely complex and not harmonised. From a water protection policy perspective, there is a need for action in both protected and non-protected areas. The authors also point out that there are numerous strictly protected species in the catchment area of the Neman River with a high demand for land. Within the framework of concrete feasibility studies, it must therefore be clarified whether peat-conserving use is possible after rewetting and which nature conservation requirements must be complied with. A valuable dataset that can be derived from the database is the "impact of drainage" – an information which is available for the whole catchment area (see tables 5 and 7).

Referring to the Paludiculture Strategy Mecklenburg-Vorpommern (LM M-V (2017), rewetting and implementing paludiculture on non-protected areas is easiest to realise on non-protected areas. For the protected areas it has to be checked if there are any restrictions against rewetting or implementation of paludiculture. Anyway on some part of the area with protection status, it should be possible to carry out rewetting and implement paludiculture (at least wet grassland for meadows or pastures) in consultation with the nature conservation authorities. Raising water tables and regular management of vegetation is a precondition for oligotrophication by export of nutrients via harvesting and site adapted biodiversity. By that this is of fundamental interest for nature conservation.

4.1.3 Drained peatlands in the Neman River basin

Peatlands are usually drained to enable conventional cultivation for agri- and silviculture as well as for peat extraction. Overall, 438,536 ha of the Neman River basin's peatlands have been drained (table 6), with Lithuania recording the largest area (299,020 ha), followed by Belarus (118,355 ha), Poland (16,012 ha), and Russia (4,889 ha) (Manton et al. 2021). About 44% of the peatlands in the whole catchment area are impacted by drainage, 56% are not affected (see table 6).

There are different degrees of degradation by drainage in the different countries. This may also be different regarding the type of peatlands. Based on the database sources, quarries, pastures, and meadows as well as agricultural land show the highest proportion of soils affected by drainage (about 30% of the total peatland area). It must be assumed, however, that the "not impacted" areas mentioned in table 6, apart from the semi-natural grasslands, are also influenced by drainage – otherwise they could not be farmed conventionally. That means that at least 438,536 hectares in the whole catchment area are degraded by drainage activities. Their status shows the great potential to be optimized by rewetting and partly by implementation of paludiculture.

Table 6: Land use on peatlands in the Neman River basin and impact by drainage

Land use	Not impacted	impacted
Agricultural land	89,283	84,485
Forest	263,094	94,436
Natural peatlands	55,476	15,104
Other	1283	765
Pastures and meadows	14,6143	114,635
Quarry	2,156	112,844
Semi-natural grasslands	6,649	9,628
Urban	64	120
Water bodies	4,119	6,518
Total	**568,266**	**438,536**

Table 7 shows the total area without protection status in the Neman River basin which is impacted by drainage per country. The greatest potential for rewetting and implementation of paludiculture are the quarries (99,729 ha), most of them situated in Belarus (86,242 ha) followed by pastures and meadows which have no protection status (91,336 ha) as well as non protected agricultural lands impacted by drainage (77.663 ha) mainly in Lithuania (71,676 ha).It is also clear that Lithuania has the greatest potential for rapid restoration of peatlands affected by drainage without any protection status (239,110 ha) from total in the Neman River basin (357,069 ha).

Table 7: Land use, protection status and area in countries of the Neman River basin impacted by drainage

	Impacted, not protected			
Land use	**BY**	**LT**	**PL**	**RUS**
Agricultural land	5.987	71.676	0	0
Pastures and meadows	10.125	80.258	953	0
Forest	8.440	57.050	522	8
Quarry	86.242	13.487	0	0
Natural peatlands	1.650	5.058	66	3.167
Semi-natural grasslands	45	5.570	615	0
Water bodies	4	5.386	17	0
Other	0	625	0	0
Urban	120	0	0	0
Total	**112.613**	**239.110**	**2.173**	**3.175**

Source: after Peatlands of Neman basin. Pivot excel sheet from M. Manton 14.1.22

Within the framework of an area-specific feasibility study, it should be examined where these areas are located and where favourable conditions exist for conversion to paludiculture. For this purpose, planning tools such as the Decision Support System described in chapter 4.6 and the suitability criteria listed in the checklist can be used.

4.3 Area potential for conversion to paludiculture

From a climate and water protection policy perspective, the rewetting of peatlands and implementation of paludiculture must focus on peatlands affected by drainage (see tables 6, 7). With reference to the use of peatland, all drained peatlands must be rewetted by 2050. Afterwards, they can be managed in a peat-conserving manner in the sense of a nature or climate based measure (European Commission 2015).

In principle, all drained peatlands are suitable for restoration of important functions for water-, climate and nature protection after rewetting. However, the entirety of agriculturally used organic soils is not available as land potential for conversion to paludiculture, as existing natural restrictions (e.g. water availability) and legally binding as well as planning requirements must be taken into account. The restoration of peatlands can aim at natural succession of vegetation with a focus on reducing GHG and nutrient emissions. However, in addition to reducing GHG emissions, the objective may also be to preserve the rewetted peatlands for biodiversity conservation or development. The maximum possible area potential for paludiculture includes both cultivated paludiculture, which is established in a targeted manner, and productively managed wet meadows and pastures, on which nature conservation services are also provided.

An analysis of potential areas, considering the different aspects of paludiculture implementation (see below) and the data base available, should reflect site conditions, current land use, and current sectoral allocation of the land (LM M-V 2017, Tanneberger et al. 2020), infrastructure and other relevant factors. Depending on the objectives of water protection, additional data (e.g., size or accessibility) must be located for suitable sites in the framework of a specific feasibility study.

4.4 Priority of areas for nutrient retention

The DESIRE-"Strategy" aims at serving water protection. Precisely for this principles and priority areas must be identified. Mires respectively peatlands are rather sensitive ecosystems which often show some status of protection or conservation. This is subject of data bases and thematic maps in most countries. Restrictions due to nature conservation objectives may exist primarily regarding the modification of the existing vegetation composition, which must be considered when planning and implementing specific rewetting projects or paludicultures. Agricultural management of rewetted areas can be targeted by cultivating and managing specific plant species adapted to the wet conditions of the peatlands ("cropping paludiculture") as well as on peatlands that have been enhanced for nature conservation purposes. In both cases, it must be ensured that the cultivation does not lead to peat decomposition.

4.4.1 Peatland restoration

Kreyling et al (2021) have quantified the success of restoration of 320 peatland sites that have been rewetted in recent decades against 243 semi-natural peatland sites of similar origin in temperate Europe. In the heavily disturbed and long drained fens, the physical parameters of the peat have changed (e.g., increased bulk density and reduced porosity, hydraulic conductivity, and water storage capacity). Against this background, it can be assumed that natural conditions will not be restored immediately after rewetting, but only after decades. From a water protection perspective, it should be noted that nutrient availability directly after rewetting is much higher than in natural peatlands, which is mainly due to peat mineralisation and fertilisation during peatland drainage and to the mobilisation of phosphorus during rewetting. The results of the study by Kreyling et al. show that there is no general trend towards natural conditions up to three decades after rewetting, that rewetted peatlands differ from semi-natural peatlands in their biodiversity and functioning, that the management of the novel ecosystems requires a functional understanding and cannot be transferred from natural systems. Instead, an interdisciplinary, process-based understanding of rewetted systems is required to prioritise, plan, and implement restoration measures and to design their sustainable management.

4.4.2 Paludiculture and nature protection

Regarding paludiculture, sown and planted reed beds which address production goals should be treated differently than natural reed beds, which are mostly listed as protected habitats, with restrictions in vegetation management. To avoid undesired developments and conflicts with the objectives of nature conservation, guidance is required for implementing paludiculture (Tanneberger et al. 2020, Tanneberger et al. 2022). In the study by Manton et al. (2021) mentioned above, the total area of land for rewetting was derived based on nature conservation requirements. This is a first and important step for the identification of land potential for biodiversity conservation or development. The nature conservation regulations describe what should be (de jure) but not the actual (de facto) condition of the land and often imply vegetation management of the sites. For the concrete planning and implementation of water protection measures, other ecosystem-relevant factors must be considered in a further step from a natural science perspective. For the quantification of nutrient retention, further ecosystem-relevant parameters must be considered in the concrete planning and implementation (see table xyz). The challenge here is that the restoration of peatlands still has numerous gaps in knowledge.

4.4.3 Influence of management on nutrient balance

The establishment of 'permanent grassland paludiculture' (wet meadows, wet pastures) can lead to a gradual change in species composition following raised water tables and management, dependent on the harvesting date and intensity of utilisation. But it will usually not conflict with nature conservation objectives. On the contrary it may precisely be through regular harvesting that the biodiversity of the site can be preserved or promoted - paludiculture then additionally requires a sensible utilization of the biomass and can lead to oligotrophication of the site. Therefore, such shift in species composition mostly would comply with existing legal or planning requirements and can even benefit nature conservation objectives. In 'cropping paludiculture', plants such as Black Alder, Common Reed, Cattail, Reed Canary Grass or other grasses or plant species are cultivated as target crop and replace the existing vegetation. On areas where the present vegetation is subject to protection, replacement by paludiculture crops is not possible. However, careful adjustment of vegetation composition to rising water levels and adapted, biodiversity supporting mowing regimes should be possible. Paludiculture can be differentiated according to the vegetation which shall be harvested. The cultivation may make some soil preparation (tillage) necessary in advance to plantation of target species. According to regional nature conservation laws, any protection status may exclude a change of the existing vegetation structure.

Table 8: Selected information needs for the assessment of nutrient retention through conversion to paludiculture (….)

Nutrient balance
Nutrient inputs from the catchment area (groundwater and surface water)
Current runoff and nutrient loads from the area (water balance and annual average loading rates kg N and P per ha)
Relevance of P release through rewetting (hydrogenetic peatland type, presence of shallow lakes with active mud formation, state of degradation, connection to surface waters and receiving water)
Relevant DOC release through rewetting (use, hydrogenetic peat type, connection to surface waters and receiving water)
Avoidance of nutrient removal through water level elevation (annual average removal rates kg N and P per ha)
Nutrient removal through harvesting (annual average removal rates kg N and P per ha and year)

4.4.4 Necessary measures to be taken to rewet peatlands and to the conversion to paludiculture

There are several steps on the way to rewetting and implementing paludiculture on formerly drained peatlands. In different countries they are similar, the design of these steps may differ in different countries:

- Decision making for peatland rewetting and/or change to paludiculture
- Spatial, hydrological and technical planning of measures, project design
- Permits and authorizations
- Earthworks
- Active raising of water levels, planting of target vegetation if necessary

- regular management of water level and vegetation

In parallel to these activities, a value chain must be identified and/or established that can take up the biomass to be produced in paludiculture. Either new utilisation lines have to be developed and established, or the focus is on replacing fossil raw materials in existing lines with biomass from paludiculture, for example. These different steps may take a considerable time and may require up to several years before rewetting and, if intended, the establishment of paludiculture can be realized.

4.5 From strategy to implementation planning

In countries with private ownership of the land, cooperation between stakeholders is of high importance, as decisions on the future management of peatlands almost always involve several landowners, land users and other stakeholders and interest groups. A participatory planning process needs to involve the different stakeholders and has a common knowledge base. To develop an approach that facilitates the shift from peatland drainage to greenhouse gas and nutrient emission reduction and paludiculture, a definition of land suitability classes needs to be developed (Tanneberger et al. 2022). In addition to guidance on the participatory planning procedure for rewetting and paludiculture, also risks and co-benefits must be considered as well as perspectives of spatial planning and funding framework.

In all peatlands which are impacted by drainage, rewetting should be beyond question and any paludiculture is possible (all degraded peatlands outside protected areas). Also, in protected areas we find sites which are impacted by drainage which need some rewetting for reduction of nutrients- and GHG emissions. Depending on the requirements placed on the vegetation management of peatlands in these protected areas only permanent wet grassland paludiculture is possible and an administrative check is needed to safeguard nature protection goals. A site-specific check by relevant authorities is needed to safeguard nature protection goals. Also, a complete restriction is possible (e.g., core zones of biosphere reserves or national parks.

4.6 Peatland restoration and implementation of paludiculture in the River Basin Management plans for the Neman River Basin

Any implementation of rewetting measures and paludiculture should be in line with any landscape framework plan, land use planning or with any other corresponding planning bases like water framework directive or river basin management plans (if these instruments exist in the respective countries). A major weakness is that most of these plans do not address the use of peatlands at all.

The context described above shows that there are many reasons why peatlands themselves, but also peatland protection, rewetting, and implementation of paludiculture should be considered in the River Basin Management plans (RBMPs) of the countries contributing to the Neman catchment area. It should be acknowledged that peatland´s function can be restored from being a source of nutrients to a sink – and, besides many other positive effects, a considerable reduction of nutrients loads could be reached by including the peatlands issue into the RBMPs. Exemplarily there has been elaborated a blueprint for the Polish part of the RBMP which shows, at which sections peatlands should be considered within the RBMP (2.4_BLUEPRINT Poland.pdf (moorwissen.de)). An analysis of the RBMP for the Lithuanian part of the Neman River and discussion shows, how peatland rewetting as a measure for improvement of water quality could be considered (Trehan 2020; RMBP-report-1.pdf (moorwissen.de)).

The preceding chapters have shown that an overlap of the different political binding targets is in most cases given in a synergistic way. However, conflicts of objectives between climate, biodiversity, and water protection (e.g., release of phosphorus after rewetting) may arise, which must be identified when planning concrete rewetting measures. The retention effect, which is important for water protection, is determined to a large extent by the hydrological and hydrogeological integration of a peatland in the landscape. In the concrete implementation of measures, these targets must be examined and coordinated within the framework of a feasibility study so that the right measures on specific sites can be considered at the right time. However, a strategy is not about planning concrete measures, but about managing policy objectives in a forward-looking way and in outlining possible ways to achieve the objectives, the challenges involved and identifying and prioritising measures for water protection through sustainable use of peatlands.

Key principles for implementation of strategies (see Joosten & Clarke 2002, ch. 5.4 Guidance principles for wise use of peatlands, pp. 125-27, Kozulin et al. 2018, Tanneberger et al. 2020) and focus areas for rewetting of degraded peatlands until 2050 are described in the following.

Table 9: Checklist on the information requirements of feasibility studies for the rewetting of peatlands and conversion to paludiculture

Legal framework for rewetting and paludiculture
- Conservation area
- Legally protected biotopes
Area and habitat requirements
- Area of bogs, fens, and transgression mires
- Soil characteristics (soil class and type)
- Degree of topsoil degradation (0 - 30 cm)
- Hydrological regime
- Water regime (mean ground water table distance, rewettability)
- Partial or complete water level elevation
- Land available for paludiculture after water level elevation
- Creation (constructed wetlands or wetland buffer zones) or restoration of wetlands
- Cultivation of suitable peat-conserving wetland plants
Status-quo of current land use
- Type of agricultural use
- Size of the area in relation to the catchment area
- Water management (e.g., pipe drainage, pumping stations)
- condition of technical facilities, age of water management facilities and need for renewal
Technical demands for cultivation of paludiculture
Rewetting ability (water yield and management, peat depth)
Water level regulation
Logistical and infrastructural requirements (road infrastructure, plot size)
Technical requirements for the further processing of paludiculture biomass
- Demand potential
- Suitable utilisation paths
- Processing companies
- Distance to potential markets / consumers

Source: modified after Schlattmann & Rode 2019.

The description of the spatial planning procedure according to the decision support tool from Schlattman & Rode (2019) shows a possible approach (table 9). There are several tools available to select suitable areas for rewetting (Knieß 2007, Abel et al. 2011, Schulze et al. 2016). They comprise e.g.

bottom-up decision support tools (e.g., DSS TORBOS, Servi-peat, Clearance nutrient tool). The decision support system for peat-conserving management of organic soils (DSS TORBOS, see figure 3) provides site-specific advice and recommendations for fen sites. Furthermore, the impact on the peatland site in terms of peat conservation and greenhouse gas emissions is estimated and the impact on biodiversity is assessed. The recommendations, which are systematically derived according to a bottom-up approach, are primarily aimed at farm managers and their advisors.

Selected usable databases for primary planning for peatland rewtting activities

- Digital elevation model
- Historic maps
- Maps on geology, soil types, topography and maps on geological resources
- Hydrological maps, amelioration plans, hydrologic and metereologic datasets
- Data on biotope types, forestry mapping, FFH sites and management plans, nature conservation requirements, land cadastres, Eco accountings, compensations
- Data bases on flora and fauna, Surveys on species and habitat protection
- Data on infrastructure, pipeline routes, property, uses and landscape planning

A decision tree is a hierarchical series of questions to guide a decision concerning an object or a process. Each question concerns an attribute of the object or a process, and prompts an answer that affects the further path through the tree. Going through the tree, attributes with the largest information content are addressed first, followed by the next most relevant, and so on.

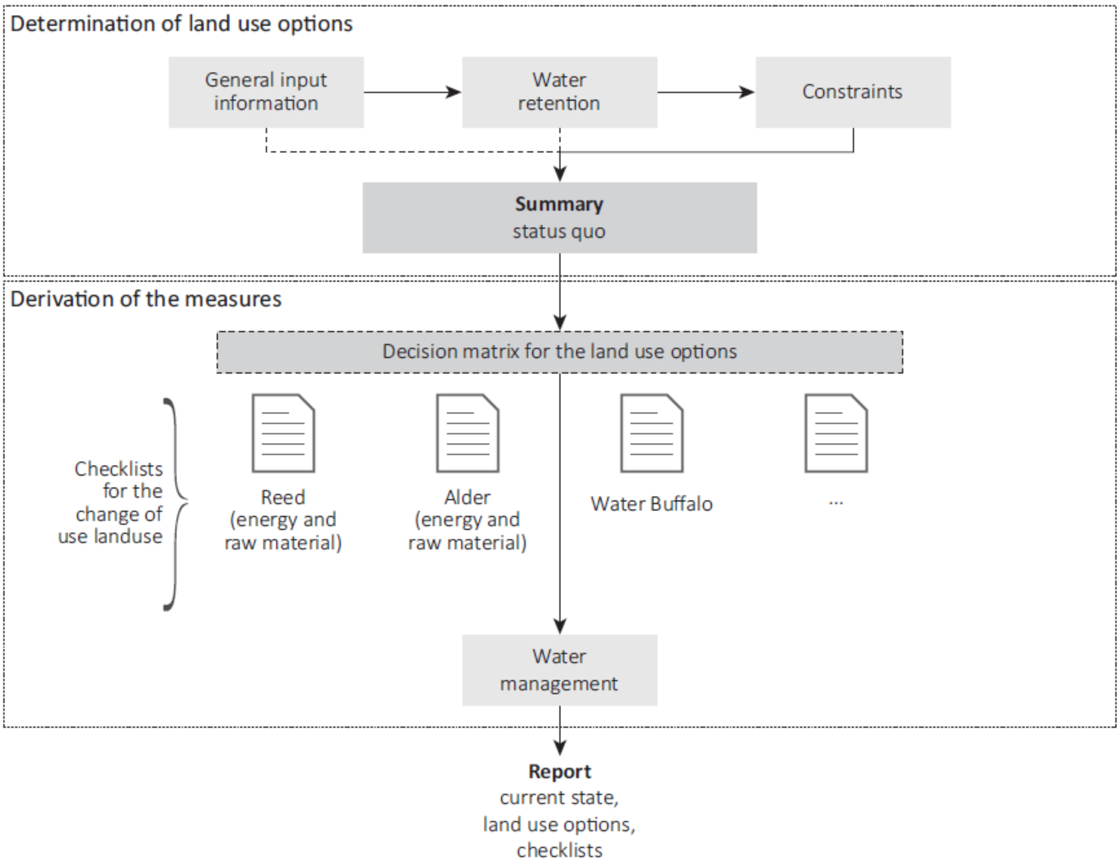

Figure 3: Basic structure of the decision support system TORBOS (the acronym stands for peat preserving cultivation of organic soils; German: Decision Support System zur TORferhaltenden Bewirtschaftung OrganiScher Böden), Schulze et al. (2016).

Attributes can be expressed either on a categorical scale or a metric scale. Through its hierarchical structure and by reducing decisions to a single attribute at a time, a decision support tree (example see Figure 3) allows its user to make a quick, substantiated decision (Schulze et al. 2016).

5 Economic assessment for peatland restoration and conversion to paludiculture

5.1 Theoretical and realisable potentials for paludiculture – analysis of weak points

The land potentials for conversion to paludiculture presented in chapter 4 differ depending on the climate, nature, and water protection goals to be considered. There is no question that rewetting in many cases creates synergy effects: An increased water level in a formerly drained peatland not only reduces GHG emissions, but also promotes the protection of endangered biotopes and peatland-typical animal and plant species and reduces the eutrophication of aquatic ecosystems by retaining nutrients. These welfare-relevant ecosystem services are provided by rewetting. With the conversion to paludiculture, additionally the production function can be maintained and the harvesting of the paludi-biomass results in a water protection-relevant withdrawal of nutrients.

The rewetting of drained peatlands, which is necessary for climate and water protection policy, is an imperative prerequisite for conversion to paludiculture. The land potential for conversion to paludiculture presented in chapter 4 are a theoretically possible upper limit. In connection with biomass use and the development of new and not yet existing value chains, a fundamental distinction can be made between theoretical, technical, economic, and realisable potential. With each gradation, the potential generally becomes smaller, as the residual friction increases. **Theoretical potential** is understood as the maximum possible implementation of a technology resulting from the entire supply or demand, including new technologies to be expected in the future.

From an economic perspective, several constraining potential factors are relevant for conversion to paludiculture from both the supply and demand sides. The potential factors can be seen as a bundle of potential uses available over time to farms to produce paludi biomass. The potential supply of land for paludi biomass production can be systematically determined within the framework of a decision support system. The amount of land that needs to be rewetted to meet climate change policy targets by 2050 is a suitable starting point for determining the theoretically usable land potential for conversion to paludiculture. However, not all areas are suitable for conversion to paludiculture after rewetting. There are major technical and logistical challenges in the cultivation of large areas and productive stocks. The **technical potential** results from the theoretical potential, considering technical, infrastructural, and ecological constraints as well as temporal and spatial discrepancies between supply and demand.

In a first step, it is therefore necessary to check which areas are available for conversion to paludiculture after rewetting. The hydrological planning must also identify areas that will be permanently flooded after rewetting due to advanced degradation of the peatlands and cannot be used for paludiculture. There is still a need for discussion regarding the production of aquatic plants or fish in rewetted, fully inundated peatlands and their compatibility with the principles of paludiculture, especially according to their greenhouse gas emissions. It must also be checked whether there is sufficient water available when it is needed, or whether the water supply in the catchment area is a limiting potential factor. This may be due, for example, to a lack of or insufficient water inflow or if water losses within the peatland (evaporation, seepage) cannot be sufficiently compensated by water retention. For the conversion to paludiculture, a sufficient water supply must be ensured also from an economic point of view to reduce production risks for the specific paludiculture methods, especially in dry years, which are to be expected more frequently in the future because of the ongoing climate catastrophe. Further restrictions that limit the amount of agricultural land are the framework conditions of nature conservation law (see chapter 4) and water protection policy targets of the Water Framework Directive (e.g., avoidance of an impairment of sensitive water bodies through increased phosphorus input or ensuring the continuity of watercourses).

Once it has been clarified which peatlands allow peat-conserving management according to the site conditions and which nature conservation and water protection-related restrictions must be observed, technical cultivation measures and possible management options can be planned for the implementation of paludiculture on the areas in question. For the cultivation and removal of the biomass, an adapted transport infrastructure is required, which reduces the production area. The permanently available rewetted areas that can be converted to paludiculture then make up the total land supply on which pauldi biomass can be produced. The limited technical, logistical, and organisational framework conditions of agricultural and forestry biomass production reduce the supply of usable paludi biomass.

The **economic potential** is the share of the technical potential that can be used from an economic or business perspective, considering any subsidies. Economic use requires not only high, but also long-term investments in machinery and technology, as well as an expansion of the infrastructure. For farm managers who want to convert their production from drainage-based peatland use to peat-conserving paludiculture, the main question is therefore whether there is any solvent demand for paludi-biomass at all. For the processing companies, the question is what marketable paludi-products can be made from it. The targeted cultivation and utilisation of biomass is a novelty and so far, only marginally established in niche markets. The economic viability of potentially suitable paludiculture practices depends heavily on future demand, which is currently insufficient. Therefore, the economic analysis of the conversion to paludiculture and the derivation of suitable economic policy instruments must consider not only the supply side but also the demand side.

The **realisable potential** is the part of the economic potential that can ultimately be realised under the given boundary conditions (e.g. legal and administrative barriers, limited availability of investment funds, lack of information).

5.2 Contribution of paludiculture to a sustainable circular economy

Because raw materials from paludiculture are only worthy of transport to a limited extent, regional processing into intermediate and end products makes sense not only from an ecological point of view. However, paludiculture offers the possibility to continue using peatlands for agriculture and forestry after the water level has been raised, thus contributing to a sustainable circular economy (Tanneberger et al. 2020a). In this way, an added value can be created in the structurally weak rural areas of the Neman River basin.

Agricultural utilisation, energetic and material use in industry and handicraft can be distinguished as options for utilization of biomass from paludiculture (see chapter 3.4; Närmann et al. 2021). However, for most of the uses described in chapter 3, there is no demand yet. Nevertheless, paludiculture should be seen as an integrative system solution for sustainable development, where it is essential to also shed light on the utilisation options. After more than 300 years of drainage-based peatland use, the targeted cultivation and utilisation of biomass from wet peatlands is a novelty. The utilisation of biomass has so far only been marginally established in niche markets (e.g., reed production for roofing or grazing with water buffaloes). From an economic point of view the situation is paradox. The development of paludi products into which Paludi biomass can be further processed is an important key to further processing. Because without further processing of paludi biomass, there is no cultivation. And vice versa: without cultivation of Paludi biomass, there is no further processing (chicken-and-egg problem). And on top of that: without Paludi products, there is no value creation.

Although the concept of paludiculture is known for more than 20 years, first small-scale scientifically motivated pre-commercial pilot projects for the establishment of paludiculture have been realised so far (Ziegler et al 2021). Here on small scale, data on the use of adapted cultivation and harvesting techniques and on water management, for example, could and can continue to be collected to derive valuable recommendations for further implementation of paludiculture. Exemplary and innovative utilisation- and processing lines can also be tested and further developed at this scale. For addressing the major societal challenges in the reorientation of peatland use, large-scale implementation can make a valuable contribution to a sustainable circular economy. The next steps would then be the preparation and realisation of large-scale, hydrological units rewetting of peatlands and measures for conversion to paludiculture.

A large market potential is seen in the building materials sector, e.g. to provide biomass for the production of construction panels and insulation materials (Staniaszek et al. 2015). One of the most important future climate policy challenges in the building sector is the refurbishment of buildings and the reduction of energy consumption of insulation materials during all life phases, from production to demolition ("cradle to cradle"). Most of the building insulation is still made from resource materials that are produced with a high energy input (glass and mineral insulation materials) or from fossil raw materials from the petrochemical industry (mainly polystyrene) (Lahtinen et al. 2022). Therefore, the climate protection policy requirements and the demand potentials for new construction and renovation of buildings are extraordinarily large. This results in enormous and yet recognized sales markets for the utilisation of paludi-biomass.

However, the development of the theoretically available land and demand potential for a sustainable circular economy through paludiculture will only succeed if the farmers and processors have the prospect of earning a sustainable income by paludiculture. From the farmers point of view, the conversion from drainage-based agricultural peatland use to paludiculture involves additional investments and risks, and they need above all clear signals from the markets that what they produce on wet peatlands will also be demanded and rewarded. Because not only the technological change in the cultivation of biomass and its further processing, but also the market introduction of paludi-products currently still represents real obstacles to implementation, work must also be done on the further processing of paludi biomass and the development of paludi-products at the same time as promoting the establishment of paludiculture.

For paludiculture, to make its contribution to a circular bioeconomy, the barriers to implementation from cultivation on the land to the use of the products, must be overcome in the difficult phase of market introduction. The market launch phase is very cost-intensive and in most cases has a rather negative impact on profits because farmers and processors must first invest in research and development measures and cannot yet generate cost-covering income from the sale of the products. To overcome the difficult phase up to successful market entry, additional targeted flanking financing instruments must be developed and brought into application to overcome the "valley of death" as the most critical phase of the product life cycle. This includes, above all, innovation, and investment support, which should be used to promote research and development in the cultivation of paludi biomass and the market launch of climate-friendly paludi products. To reduce the existing obstacles to conversion to paludiculture, farmers and processors will need appropriate financial incentives and accompanying support for a transitional phase, like the politically desired promotion of organic farming or the market introduction of renewable energies.

5.3 Costs and benefits of rewetting and conversion to paludiculture

Rewetting of peatland area and conversion to paludiculture is connected with different costs and benefits, dependent on several site specific and administrative challenges. The following aspects give a rough overview.

Some cost relevant points are e.g.:

- Economic evaluation (Comparison of scenarios, with-without project comparison)
- Rewetting costs
- Costs for establishment of paludiculture plant species, maintenance, harvesting, and processing facilities
- Opportunity costs
- Marginal and total abatement cost of nitrogen, phosphorus, and carbon
- Benefits of rewetted peatlands (reduced eutrophication and recreation services)

On the other hand the following benefits can be considered:

- Environmental gains like nutrients reduction and GHG emissions reduction
- Incomes from biomass utilisation
- Other incomes due to rewetting and paludiculture

5.4 Financing instruments for rewetting and conversion to paludiculture

In different countries different instruments for financing measures for rewetting and paludiculture are available. In most cases such things are not on the daily agenda, neither with administrations nor with representatives from agriculture. On the contrary:

- Rewetting of peatlands and conversion to paludiculture requires a paradigm shift
- There are different conditions for area-, farm- and product-related starting points
- Appropriate financing and steering instruments for rewetting and conversion to paludiculture are rather differentConsidering EU and non EU-countries is an extra challenge due to rather different regulations

Recommendations for the design of financing instruments must be developed which provide guidance in the respective countries on how funding instruments can be designed. The DESIRE project has already developed proposals for the design of agri-environmental and -climate programmes for the EU countries Lithuania and Poland. By such tools the maintenance of rewetted peatland sites by regular vegetation management can be guaranteed as long as these are contractually secured within these programmes. As well important are the development of funding schemes for activities on the ground in connection with the restoration and of the hydrological regime and maintenance of the wet conditions of the site as a prerequisite for the implementation and performance of paludiculture. Paludiculture and the value it can create as a nature-based solution can provide new incentives in the regions and serve as a basis for development of new rural activities.

6 Conclusion and recommendations

The DESIRE-strategy for nutrient reduction and implementation of paludiculture in the Neman River basin including economic assessment is the first step for a peatland-based estimation of nutrient reduction on the scale of a whole catchment area of a medium sized river system. The available database (Manton et al. 2020) allows a quick overview to assess areas that can or should be rewetted for nutrient reduction. Quantification of the potential impact of rewetting measures and conversion to paludiculture on nutrient reduction in the surface waters of the Neman River basin needs to be done in the context of area-based feasibility studies.

A preliminary evaluation of the available data is presented in chapter 4. It calculates potential areas of peatlands to be rewetted and brought into paludiculture, taking into account the type of peatlands, their current use, their protection status and their impact by drainage. Of course, this is an assessment on the basis of files and search areas can certainly be identified initially. In addition, on-site investigations of the soil, the hydrological characteristics of the site and other site-specific data are required to be collected at the site (ground trothing), which must take into account the ecological and geohydological charachteristics of the peatland site and the possibility of rewetting, the usefulness of paludiculture and the general conditions.

Future steps which should be taken in the countries of the whole catchment area of the Neman River if they care about improving water quality, as soon as possible:

- Inclusion of peatland issues into the River Basin Management Plan of Neman River
- Design of the framework conditions for the simplified implementation of rewetting measures and paludicultures
- Develop incentives for nutrient retention by paludiculture
- Optimise framework conditions for market introduction and development of paludi-products
- Check the data base and verify the situation by ground truthing
- Select sites to be rewetted / turned to paludiculture
- Begin with first steps of rewetting and implementation of paludiculture as early as possible

Which data are important for private and political decision-makers for an effective water protection policy?

The data base of Neman peatlands (Manton et al. 2021) provides dat sets which can be used for preliminary assessment of potential areas for implementation of paludiculture in the whole Neman river basin within an top don approach. Further specification will make some ground trothing necessary to be able to designate specific areas for rewetting and paludiculture.

Consequences for the Neman River basin

- Peatlands should be considered in planning documents (RBMP, WFD, ….). Among a large number of ecosystem services as a way to mitigate nutrients with natural processes in the Neman River
- Cooperation of countries contributing to the river catchment should be intensified to advance catchment-based solutions
- National government incentives should be created and offered to stakeholders who are willing to implement innovations in the region. This, in remote regions, will result in developing further and becoming economically stable regional conditions.

It must be stated that there are still several knowledge gaps and that there is a need for further research. But this should not stop us from starting to implement rewetting measures and introducing paludiculture wherever indicated. The current science-based knowledge which has been reviewed in previous sections of this manuscript on the mitigation of emissions of nutrients and greenhouse gases from peatland catchments and the purification effect of wetlands for inflowing polluted water is sufficient to justify these measures. Country specific incentives must urgently be developed. These incentives for agriculture and administrations must be introduced in the very short term so that corresponding positive results in reducing emissions can be achieved in due time.

7 Sources

Abel, S., Couwenberg, J., Dahms, T. & Joosten, H. (2013): The Database of Potential Paludiculture Plants (DPPP) and results for Western Pomerania. – Plant Diversity and Evolution 130: 219–228

Abel, S., Haberl, A. & Joosten, H. (2011): A decision support system for degraded abandoned peatlands illustrated by reference to peatlands of the Russian Federation. Michael-Succow-Stiftung zum Schutz der Natur, Greifswald.

Audet, J., Zak, D., Bidstrup, J., Hoffmann C.C. (2020): Nitrogen and phosphorus retention in Danish restored wetlands. Ambio 49, 324–336, https://link.springer.com/article/10.1007/s13280-019-01181-2

Birr, F., Abel, S., Kaiser, M., Närmann, F., Oppermann, R., Pfister, S., Tanneberger, F., Zeitz, J., Luthardt, V. (2021): Zukunftsfähige Land- und Forstwirtschaft auf Niedermooren. Steckbriefe für klimaschonende, biodiversitätsfördernde Bewirtschaftungsverfahren. Hochschule für Nachhaltige Entwicklung und Greifswald Moor Centrum, Eberswalde, Greifswald.

Carstensen, M.V., Hashemi, F., Hoffmann, C.C., Zak, D., Audet, J., Kronvang, B. (2020): Efficiency of mitigation measures targeting nutrient losses from agricultural drainage systems: A review, Ambio 49, 11, pp. 1820-1837.

Čerkasova, N., Umgiesser, G., Ertürk, A. (2021): Modelling framework for flow, sediments and nutrient loads in a large transboundary river watershed: A climate change impact assessment of the Nemunas River watershed, Journal of Hydrology, 598, 126422, ISSN 0022-1694, https://doi.org/10.1016/j.jhydrol.2021.126422.

Czubaszek, R., Wysocka-Czubaszek, A., Wichtmann, W., Banaszuk, P. (2021): Specific methane yield of wetland biomass in dry and wet fermentation technologies. Energies 14, 8373. https://doi.org/10.3390/en14248373.

Dahms, T., Oehmke, C., Kowatsch, A., Abel, S., Wichmann, S., Wichtmann, W. & Schröder, C. (2017): Halmgutartige Festbrennstoffe aus nassen Mooren. Universität Greifswald, Greifswald Moor Centrum. 73 S. (2. Auflage)

Dawson, L., Elbakidze, M., Schellens, M., Shkaruba, A., Angelstam, P.K. (2021): Bogs, birds, and berries in Belarus: the governance and management dynamics of wetland restoration in a state-centric, top-down context. Ecology and Society 26, 1, 8. https://doi.org/10.5751/ES-12139-260108

Estreguil, C., Dige, G., Kleeschulte, S., Carrao, H., Raynal, J., Teller, A., (2019): Strategic green infrastructure and ecosystem restoration, EUR 29449 EN, Publications Office of the European Union, Luxembourg. https://doi:10.2760/36800

European Commission (2015): Towards an EU research and innovation policy agenda for nature-based solutions & re-naturing cities: Final report of the Horizon 2020 expert group on "Nature-based solutions and re-naturing cities." Publications Office of the European Union. https://doi.org/10.2777/765301

Gailiušis, B.; Jablonskis, J.; Kovalenkoviene, M. (2001): The Lithuanian rivers. In ˙ Hydrography and Runoff; Lithuanian Energy Institute: Kaunas, Lithuania; 792p, ISBN 9986-492-64-5
Geurts, J., Oehmke, C., Lambertini, C., Eller, F., Sorrell, B., Mandiola, S.R., Grootjans, A., Brix, H., Wichtmann, W., Lamers, L., Fritz, C. (2020): Nutrient removal potential and biomass production by Phragmites australis and Typha latifolia on European rewetted peat and mineral soils. Science of the Total Environment. DOI: 10.1016/j.scitotenv.2020.141102
Geurts, J.J.M., van Duinen, G.-J.A., van Belle, J., Wichmann, S., Wichtmann, W., Fritz C (2019): Recognize the high potential of paludiculture on rewetted peat soils to mitigate climate change. Journal of Sustainable and Organic Agricultural Systems 69:5–8. doi:10.3220/LBF1576769203000
Global Environment Facility (2021): Fostering Multi-country Cooperation over Conjunctive Surface and Groundwater Management in the Bug and Neman Transboundary River Basins and the Underlying Aquifer Systems. Accessed 04.11.2021: https://www.thegef.org/project/fostering-multi-country-cooperation-over-conjunctive-surface-and-groundwater-management-bug.
HELCOM (2008): Voluntary Report on Implementation of the Programme of Work on Marine and Coastal Biological Diversity, Draft HELCOM BIO report, 2008-11-12.
HELCOM (2018): HELCOM Thematic assessment of eutrophication 2011-2016. Baltic Sea Environment Proceedings No. 156. http://www.helcom.fi/baltic-sea-trends/holistic-assessments/state-of-the-baltic-sea-2018/reports-and-materials/
Hoffmann, C.C., Zak, D., Kronvang, B., Kjaergaard, C., Carstensen, M.V., Audet, J. (2020): An overview of nutrient transport mitigation measures for improvement of water quality in Denmark. Ecological Engineering, 105863. doi:10.1016/j.ecoleng.2020.105863.
Holden, J., Chapman, P.J., Labadz, J.C. (2004): Artificial drainage of peatlands: hydrological and hydrochemical process and wetland restoration, Progress in Physical Geography 28, 1, 95-123.
Jabłońska, E., Winkowska, M., Wiśniewska, M., Geurts, J., Zak, D., Kotowski, W. (2020): Impact of vegetation harvesting on nutrient removal and plant biomass quality in wetland buffer zones. Hydrobiologia 848, 3273-3289, doi: 10.1007/s10750-020-04256-4 .
Jabłońska, E., Wiśniewska, M., Marcinkowski, P., Grygoruk, M., Walton, C.R., Zak, D., Hoffmann, C.C., Larsen, S.E., Trepel, M., Kotowski, W. (2020): Catchment-scale analysis reveals high cost-effectiveness of wetland buffer zones as a remedy to non-point nutrient pollution in North-Eastern Poland. Water 2020 12, 629, https://www.mdpi.com/2073-4441/12/3/629.
Joosten, H., Tanneberger, F. & Moen, A. (Hg.) (2017): Mires and peatlands of Europe. Stuttgart, Germany: Schweizerbart Science Publishers, Stuttgart.
Knieß, A. (2007): Development and application of a semi-quantitative decision support system to predict long-term changes of peatland functions. Christian-Albrechts-Universität, Kiel.
Koszulin, A.; Tanovitskaya, N.; Minchenko, N. (2018): Developing a national strategy for the conservation and sustainable use of peatlands in the Republic of Belarus. Mires & Peat 21, 1–17. https://doi.org/10.19189/MaP.2016.OMB.227
Lahtinen, L., Mattila, T., Myllyviita, T., Seppälä, J., Vasander, H. (2022): Effects of paludiculture products on reducing greenhouse gas emissions from agricultural peatlands. Ecological Engineering 105, 106502. https://doi.org/10.1016/j.ecoleng.2021.106502
Land, M., Granéli, W., Grimvall, A., Hoffmann, C.C.; Mitsch, W.J., Tonderski, K.S., Verhoeven, J.T.A. (2016): How effective are created or restored freshwater wetlands for nitrogen and phosphorus removal? A systematic review. Environmental Evidence 5: 9 https://doi.org/10.1186/s13750-016-0060-0
LM M-V (2017): Umsetzung von Paludikultur auf landwirtschaftlich genutzten Flächen in Mecklenburg-Vorpommern. Fachstrategie zur Umsetzung der nutzungsbezogenen Vorschläge des Moorschutzkonzeptes. Ministerium für Landwirtschaft und Umwelt Mecklenburg-Vorpommern, Schwerin. 98 p. Nachhaltige Entwicklung - Regierungsportal M-V (regierung-mv.de)

Lundin, L., Nilsson, T., Jordan, S., Lode, S., Strömgen, M. (2017): Impacts of rewetting on peat, hydrology and water chemical composition over 15 years in two finished peat extraction areas in Sweden. Wetlands Ecology and Management 25, 405–419. https://doi.org/10.1007/s11273-016-9524-9

Manton, M.; Makrickas, E.; Banaszuk, P.; Kołos, A.; Kamocki, A.; Grygoruk, M.; Stachowicz, M.; Jarašius, L.; Zableckis, N.; Sendžikaitė, J.; Peters, J.; Napreenko, M.; Wichtmann, W.; Angelstam, P. (2021): Assessment and spatial planning for peatland conservation and restoration: Europe's trans-border Neman River basin as a case study. Land, 10, 174. https://doi.org/10.3390/land10020174

Martens, M., Karlsson, N.P.E., Ehde, P.M., Mattsson, M. & Weisner, S.E.B. (2021): The greenhouse gas emission effects of rewetting drained peatlands and growing wetland plants for biogas fuel production. Journal of Environmental Management 277, https://doi.org/10.1016/j.jenvman.2020.111391.

Närmann, F., Birr, F., Kaiser, M., Nerger, M., Luthardt, V., Zeitz J., Tanneberger, F. (Hrsg.) (2021): Klimaschonende, biodiversitätsfördernde Bewirtschaftung von Niedermoorböden. BfN-Skript 316. Bundesamt für Naturschutz, Bonn-Bad Godesberg. https://www.bfn.de/publikationen/bfn-schriften/bfn-schriften-616-klimaschonende-biodiversitaetsfoerdernde

Närmann, F., Birr, F., Kaiser, M., Nerger, M., Luthardt, V., Zeitz, J., Tanneberger, F. (Hrsg.) (2021): Climate-friendly, biodiversity-promoting management of fen soils (in German): Klimaschonende, biodiversitätsfördernde Bewirtschaftung von Niedermoorböden. BfN Skript 616. Bundesamt für Naturschutz, Bonn-Bad Godesberg. https://www.bfn.de/sites/default/files/2021-11/Skript616.pdf.

Negassa, W., Michalik, D., Klysubun, W., Leinweber, P. (2020): Phosphorus speciation in long-term drained and rewetted peatlands of Northern Germany. Soils Systems 4, 1, https://www.mdpi.com/2571-8789/4/1/11.

Oblomkova, N. (2016): Discussion within PLC-6 about total nutrient load with Neman river. Nemunas River total nutrient load (helcom.fi)

Oehmke, C. & Abel, S (2016) Promising plants for paludicuture. In: Wichtmann, W., Schröder, C & H. Joosten (2016) Paludikultur – Bewirtschaftung Nasser Moore. Klimaschutz, Biodiversaität, regionale Wertschöpfung. Verlag Schweizerbart, pp 22 - 38

Rodzkin, A.I., Kundas, S.P., Charnenak, Y. & Wichtmann, W. (2018): The assessment of cost of biomass from post-mining peaty lands for pellet fabrication. Environmental and Climate Technologies 22, 1, 118-131, DOI: 10.2478/rtuect-2018-0008

Schlattmann, A. Rode, M. (2019): Spatial potential for paludicultures to reduce agricultural greenhouse gas emissions: an analytic tool. Mires and Peat 25, 03, 1–14, http://www.mires-and-peat.net/

Schröder, C., Dahms, T., Paulitz, J., Wichtmann, W., Wichmann, S. (2015): Towards large-scale paludiculture: addressing the challenges of biomass harvesting in wet and rewetted peatlands. Mires and Peat, Volume 16, Article 13, 1–18.

Schulze, P., Schröder, C., Luthardt, V., Zeitz, J. (2016): The decision-support tool TORBOS. In: Wichtmann, W., Schröder C., Joosten, H. (Eds.): Paludiculture — productive use of wet peatlands — Climate protection, biodiversity, regional economic benefits. Schweizerbart, Stuttgart, pp. 185-187.

Schulze, P.; Schröder, C.; Luthardt, V.; Zeitz, J. (2016): The decision support tool TORBOS. In: Wichtmann et al. (2016): Paludiculture - productive use of wet peatlands. Schweizerbart, Stuttgart, p. 185 - 187

Sweers, W., Möhring ,T., Müller, J. (2014): The economics of water buffalo (Bubalus bubalis) breeding, rearing and direct marketing. Archives Animal Breeding 57:1–11. doi: 10.7482/0003-9438-57-022

Tanneberger, F., Birr, F., Couwenberg, J., Kaiser, M., Luthardt, V., Nerger, M., Pfister, C., Oppermann, R., Zeitz, J., Beyer, C., van der Linden, S., Wichtmann, W., Närmann, F. (2022): Saving soil carbon, emissions, biodiversity, and the economy: Paludiculture as sustainable land use option in German fen peatlands. Regional Environmental Change, Special Issue

Tanneberger, F., Schröder, C., Hohlbein, M., Lenschow, U., Permien, T., Wichmann, S. Wichtmann, W. (2020): Climate change mitigation through land use on rewetted peatlands – crosss sectoral spatial planning for paludiculture in Northeast Germany. Wetlands 40, 2309–2320, https://doi.org/10.1007/s13157-020-01310-8

Tiemeyer, B., Kahle, P., Lennartz, B. (2006): Nutrient losses from artificially drained catchments in North-Eastern Germany at different scales. Agricultural Water Management 85, 47-57.

Trehan, M., Wichtmann, W., Grygoruk, M. (2022): Assessment of nutrient loads into the river Ryck and options for their reduction. Water 2022, 14(13), 2055; doi.org/10.3390/w14132055

Trepel, M., Palmeri, L. (2002): Quantifying nitrogen retention in surface flow wetlands for environmental planning at the landscape-scale. Ecological Engineering 19, 127-140

United Nations Economic Commission for Europe (UNECE). (2015). Accessed 04.11.2021: https://unece.org/info/publications/pub/21676.

United Nations Economic Commission for Europe (UNECE). (2020). Accessed 04.11.2021: https://unece.org/environment-policy/water/areas-work-convention_protocol/country-dialogues/belarus.

United Nations Economic Commission for Europe (UNECE). Разработка приоритетных компонентов международного плана управления речным бассейном реки Неман/Нямунас (заключительный отчет – этап 2). (2018). [Elaboration of Priority Components of the Transboundary Neman/Nemunas River Basin Management Plan]. Accessed 04.11.2021: https://unece.org/DAM/env/documents/2018/WAT/05May_15_Minsk/Report_Neman_Phase_2_final_RUS.pdf.

Vroom, R.J.E., Xie, F., Geurts, J.J.M., Choinowska, A., Smolders, A.J.P., Lamers, L.P.M., Fritz, C. (2018): Typha latifolia paludiculture effectively improves water quality and reduces greenhouse gas emissions in rewetted peatlands. Ecological Engineering 124: 88-98. https://www.sciencedirect.com/science/article/abs/pii/S092585741830346X

Vroom, R.J.E.; Geurts, J.J.M.; Nouta, R.; Borst, A. C. W.; Lamers, L. P. M. & Fritz, C. (2022):Paludiculture crops and nitrogen kick-start ecosystem service provisioning in rewetted peat soils. *Plant Soil* 474, 337–354 https://doi.org/10.1007/s11104-022-05339-y

Vybernaite-Lubiene, I., Zilius, M., Saltyte-Vaisiauske, L. & Bartoli, M. (2018): Recent trends (2012–2016) of N, Si, and P Export from the Nemunas river watershed: loads, unbalanced stoichiometry, and threats for downstream aquatic ecosystems, Water 10, 9, 1178 DOI: 10.3390/w10091178.

Walton, C. R., Zak, D., Audet, J., Petersen, R. J., Lange, J., Oehmke, C., Hoffmann, C. C. (2020): Wetland buffer zones for nitrogen and phosphorus retention: Impacts of soil type, hydrology and vegetation. Science of The Total Environment, 138709. doi:10.1016/j.scitotenv.2020.1387

Walton, C.R., Zak, D., Audet, J., Petersen, R.J., Lange, J., Oehmke, C., Wichtmann, W., Kreyling, J., Grygoruk, M., Jabłońska, E., Kotowski, W., Wiśniewska, M.M., Ziegler, R. & Hoffmann, C.C. (2020): Wetland buffer zones for nitrogen and phosphorus retention: Impacts of soil type, hydrology and vegetation. Science of the Total Environment, https://doi.org/10.1016/j.scitotenv.2020.138709

Wassen, M.J., Olde Venterink, H. (2009): Comparison of nitrogen and phosphorus fluxes in some European fens and floodplains. Applied Vegetation Science 9, 213–222.

Wenzel, M., Kabengele, G., Dahms, T., Barz, M. Wichtmann, W. (2022): Bioenergie aus nassen Mooren -Thermische Verwertung von halmgutartiger Biomasse aus Paludikultur. Institut für Botanik und Landschaftsökologie, Unversität Greifswald.

Wichmann, S. & Köbbing, J.F. (2015): Common reed for thatching—A first review of the European market. Industrial Crops and Products 77, 1063–1073

Wichmann, S. (2018): Commercial viability of paludiculture: A comparison of harvesting reeds for biogas production, direct combustion, and thatching. Ecological Engineering 103: 497-505.

Wichmann, S. (2018): Economic incentives for climate smart agriculture on peatlands in the EU. University of Greifswald, Partner in the Greifswald Mire Centre. Report.

Wichtmann, W., Schröder, C., Joosten, H. (2016): Paludiculture – productive use of wet peatlands. Climate protection - biodiversity - regional economic benefits. Schweizerbart. Stuttgart.

Zak, D., Gelbrecht, J. Zerbe, S. Shatwell, T., Barth, M., Cabezas, A. Steffenhagen, P. (2014): How helophytes influence the phosphorus cycle in degraded inundated peat soils: implications for fen restoration. Ecological Engineering 66: 82–90. https://doi.org/10.1016/j.ecoleng.2013.10.003.

Zak, D., Wagner, C., Payer, B., Augustin, J., Gelbrecht, J. (2010): Phosphorus mobilization in rewetted fens: The effect of altered peat properties and implications for their restoration. Ecological Applications 20, 1336–1349.

Ziegler, R. (2020): Paludiculture as a critical sustainability innovation mission. Research Policy 49: 103979, https://doi.org/10.1016/j.respol.2020.103979

Ziegler, R., Wichtmann, W., Abel, S., Kemp, René, Simard, M., Joosten, H. (2021): Wet peatland utilisation for climate protection – An international survey of paludiculture innovation. Cleaner Engineering and Technology 5, December 2021, 100305, doi:https://doi.org/10.1016/j.clet.2021.100305