The economics of paludiculture: Costs & benefits of wet land use options for degraded peatlands

— with a focus on Reed and *Sphagnum* moss —

I n a u g u r a l d i s s e r t a t i o n

zur

Erlangung des akademischen Grades eines

Doktors der Naturwissenschaften (Dr. rer. nat.)

der

Mathematisch-Naturwissenschaftlichen Fakultät

der

Universität Greifswald

vorgelegt von

Sabine Wichmann

Greifswald, im Dezember 2021

Dekan:	Prof. Dr. Gerald Kerth
1. Gutachter :	Prof. Dr. Dr. h. c. Hans Joosten
2. Gutachter:	Prof. Dr. Volker Beckmann
3. Gutachter:	Prof. Dr. Sebastian Lakner
Tag der Promotion:	24.05.2022

Table of Contents

Synthesis

Original Publications

Further Material

Abstract

Drainage has commonly been a pre-requisite for the productive use of peatlands. The biased focus on agriculture, forestry and peat extraction has long ignored the destructive effects of drainage and the successive degradation of ecosystem functions of wet peatlands. Accelerated by the climate crisis, the finite nature of drainage-based peatland use is increasingly recognised. Consequently, productive land use options for wet or rewetted peatlands (paludiculture) are required as sustainable alternatives. A wide range of paludiculture plants and options of biomass utilisation are identified as suitable and promising. Despite the growing interest, experiences with and research on the economic viability of paludiculture are still rare.

This thesis addresses the lack of knowledge on paludiculture in terms of practical feasibility, costs and benefits at the farm level, market prospects and framework conditions. I selected the two currently most advanced paludicultural practices in Europe: a) Harvesting natural reed beds as a traditional 'low-input' paludiculture, i. e. the utilisation of existing 'wild' vegetation stands; b) 'Sphagnum farming' as a novel 'high-input' paludiculture including stand establishment and water management required for the active transformation from drainage-based peatland use to paludiculture. In both cases, I investigate three different biomass utilisation avenues. This thesis adds to the fields of problem-driven sustainability and land-use science. Procedures and costs of paludiculture were studied in transdisciplinary research projects in close cooperation with practitioners. Due to the novelty of the topic, I put special emphasis on the triangulation of methods and data sources: pilot trials, field measurements, semi-structured expert interviews, structured questionnaires, secondary data from trade statistics and literature. To account for uncertainty related to costs and revenues, I conduct stochastic scenario analysis (Monte Carlo simulation) for the extended contribution margin accounting of harvesting reeds and sensitivity analysis for the investment appraisal of Sphagnum farming.

Paludiculture on fens: harvesting reeds

Paper I investigates harvesting procedures for reed-dominated (*Phragmites australis*) vegetation stands. In many European countries special-purpose tracked machinery is applied for large-scale conservation management and the commercial harvest of thatching reed. Stochastic scenario analysis reveals a wide range of possible economic outcomes (ca. € — 1000 to € 1500 ha^{-1} a^{-1}) and identifies material use of reed superior to its use as a source of energy. Winter harvest of high-quality thatching reed in bundles is the most profitable option. Winter harvest of bales for direct combustion is suitable for low-quality stands and has a limited risk of loss. In the case of summer harvest, revenues for green chaff for biogas production cannot cover harvesting costs but non-market income via subsidies and agri-environmental payments may ensure profitability. While biomass for energy generation is limited to a local market, thatching reed is traded as an international commodity. The market situation for thatching reed is investigated for Europe (**Paper II**) and Germany (**Paper III**). The major reed consuming countries in Western Europe (Netherlands, Germany, UK, Denmark) rely on imports of up to 85 % of the national consumption, with reed being imported from Eastern and Southern Europe and since 2005 also from China. The total market volume for reed for thatching in Northern Germany is estimated with 3 ± 0.8 million bundles of reed with a monetary value at sales prices of € 11.6 ± 2.8 million. Most of the thatchers (70%) did not promote reed of regional origin to their customers due to insufficient availability in the first place and a lack in quality as second reason. The cultivation of reed in paludiculture may improve quantity and quality of domestic thatching reed. An area of 6000 ± 1600 ha with an average yield of 500 bundles per hectare would allow covering the current total demand of 3 million bundles of the German thatching reed market (**Paper III**).

Paludiculture on bogs: Sphagnum farming

Sphagnum farming provides an alternative to peatland degradation in two ways: Firstly, *Sphagnum* mosses can be cultivated as new agricultural crops on rewetted peatlands. Secondly, the produced *Sphagnum* biomass is a high-quality raw material suitable to replace peat in horticultural growing media (**Paper V**). Pilot trials have demonstrated the practical feasibility of establishing *Sphagnum* cultures on former bog grassland, cut-over bogs and mats floating on acidic waters bodies; **Paper IV** compares for the three types of production sites the specific procedures, costs and area potential in Germany. Water-based Sphagnum farming is not recommended for large-scale implementation due to highest establishment costs, major cultivation risks and limited area potential. For soil-based Sphagnum farming, the most important cost positions were *Sphagnum* shoots to set up pilots, investment for water management and regular weed management. Bog grassland has the highest area potential, i. e. 90,000 ha in NW Germany. **Paper V** assesses the profitability of Sphagnum farming on former bog grassland based on extrapolating five years of field experience data (establishment — management — harvest) to a total cultivation time of twenty years. Cultivating *Sphagnum* biomass as founder material for Sphagnum farming or restoration was profitable even in pessimistic scenarios with high costs, high bulk density and low yields. Selling *Sphagnum* for orchid production was economically viable in the case of medium to high yields with a low bulk density. Cost-covering prices for *Sphagnum* biomass substituting peat seem achievable if end consumers pay a surcharge of 10 % on the peat-free cultivated horticultural end-product. An area of 35,000 ha of Sphagnum farming suffices to meet the annual demand of the German growing media industry for slightly decomposed *Sphagnum* peat.

Framework conditions affecting feasibility of paludiculture

The relation of revenues from selling biomass to its production costs is an important piece of the paludiculture feasibility puzzle. Further aspects effecting the economic viability and competitiveness of paludiculture encompass the market demand, the availability of mature technology, legal restrictions, the eligibility for agricultural subsidies, a remuneration of external benefits and the opportunity costs of present farming activities (**Paper I, V**). Legal and policy regulations are of major importance for land use decisions on peatlands – both for keeping up drainage and for shifting to paludiculture.

Conclusion and Outlook

This thesis provides a first assessment of the costs and profitability of large-scale harvesting of reeds and Sphagnum farming based on real-life data. The paludicultural practices investigated may be a solution for a minor share of the more than 1 million ha of peatlands drained for agriculture in Germany. Future research should also address other biomass utilisation options and other crops. Large-scale pilots are required to improve technical maturity of procedures and machinery, gather reliable data to replace assumptions on costs and revenues and study long-term effects on economics and ecosystem services. The micro-economic perspective needs to be complemented by the societal perspective quantifying and monetising external effects of peatland restoration, paludiculture and drainage-based peatland use. There is a high need for intensified research, large-scale implementation and accelerated adaption of the policy and legal framework to develop paludiculture as an economically viable option for degraded peatlands.

1 Introduction

While about 85 % to 90 % of the global peatland area is still in a largely natural state (Joosten 2016, Leifeld & Menichetti 2018), only 54 % of the present-day peatland area in Europe and < 2 % in Germany are covered by peat forming ecosystems (Tanneberger et al. 2017a). Draining peatlands for agriculture and forestry has been the major reason for successive peatland degradation. The various negative consequences have been well known for a long time: Drainage destroys habitats of specialised and rare species, impacts the water balance of the landscape and the local climate, causes soil degradation and land subsidence, increases the risk of fire and flooding, and leads to enormous nutrient and carbon emissions. Rewetting stops degradation, may initiate the restoration of ecosystem functions resembling those of natural peatlands and benefits biodiversity (Bonn et al. 2016). The economic efficiency of restoring peatland ecosystem services is increasingly recognised (e. g. Glenk & Martin-Ortega 2018). The practical implementation, however, has been limited so far. In Europe, less than 1 % of the total area of drained peatlands has been hydrologically restored (Tanneberger et al. 2017b).

The global climate crisis changed the perception of peatlands considerably, – both in science and in policy. Peatlands became acknowledged as the largest organic carbon store of the terrestrial biosphere and key for climate change mitigation despite covering only about 3 % of the global land area (Joosten 2015, Crump 2017, Humpenöder et al. 2020, Evans et al. 2021). Expanding drainage has around 1960 turned the global peatland biome from a net sink into a net source of greenhouse gases (Leifeld et al 2019). At the global scale, present-day drained peatlands emit 2.6 %–3.8 % of all anthropogenic greenhouse gas emissions (Humpenöder et al. 2020) and further degradation and a share of 8 % in 2050 are expected (Urák et al. 2017). At a regional scale, the impact of peatlands is more obvious. In the northeast German federal state of Mecklenburg-Vorpommern, drained peatlands cause one third of the total emissions and are the single largest source of GHG emissions (Hirschelmann et al. 2020).

The Paris agreement has set a clear target of limiting global temperature rise to well below 2°C compared to pre-industrial level, preferably to 1.5°C (UN 2015). Climate-responsible peatland management requires a) conserving intact wet peatlands, b) rewetting drained peatlands and c) adapting peatland use to raised water levels (Biancalani & Avagyan 2014, Evans et al. 2021). In contrast to the former practice of only protecting and restoring selected peatlands (for Europe cf. Tanneberger et al. 2017b), every peatland has now become important (Barthelmes et al. 2015). The Paris climate target translates in a reduction of CO_2 emissions to net zero around the year 2050 (IPCC 2018) and thus implies for Germany the rewetting of an average of almost 50,000 ha of arable land and grassland every year within the next three decades (Tanneberger et al. 2021). Obviously, land use changes of this magnitude can only be managed in cooperation with farmers, landowners and the local people living in peatland-rich regions and have to take the socio-economic benefits currently derived from drained peatlands (like income and employment in rural areas, Schaller et al. 2018) into account. Consequently, paludiculture as a land use concept for rewetted peatlands is receiving increasing attention, because it addresses the need of both emissions reductions and rural livelihoods.

Paludiculture is the productive use of wet or rewetted peatlands in a way that the peat carbon reservoir is preserved and CO_2 emissions are minimized. Paludiculture has the potential to avoid or reduce manifold dis-services connected to drainage-based peatland use (cf. Wichtmann et al. 2016). The term ‘paludi-culture’ was coined in the 1990ies based on the Latin words ‘palus’ (swamp) and ‘cultura’ (care, cultivation) in analogy to established terms like ‘agri-culture’, ‘horti-culture’ and ‘silvi-culture’. The term was initially introduced for growing slightly humified *Sphagnum* peat on a rotational basis as a renewable resource for horticulture (Joosten 1998). The definition was later broadened to include all climate-friendly production of biomass on wet and rewetted peatlands (Wichtmann & Joosten 2007). In contrast to drainage-based productive use or abandonment after rewetting, paludiculture can balance provisioning, regulating, and cultural ecosystem services (Luthardt & Wichmann 2016). The worldwide growing interest in paludiculture is reflected by intensified research activities with the focus being on Europe (Geurts et al. 2019, Mulholland et al. 2020) and South-East Asia (Tata & Susmianto 2016, Budiman et al. 2020, Uda et al. 2020, Giesen 2021, Tan et al 2021, Ziegler et al. 2021).

Providing sustainable income opportunities for peatland farmers will facilitate the necessary restoration of degraded peatland functions and ensure a just transition to a climate-friendly peatland agriculture. In addition, biomass from cultivated wetland plants can provide valuable, renewable raw materials to contribute to decarbonising the economy. The global 'Database of Potential Paludiculture Plants' (DPPP) currently contains 1128 plant species that thrive under wet conditions and have a potential to be used as food, fodder, medical plants, raw material for industrial processing, fuel or growing media. Markets for products made of the above-ground biomass of 250 of these species already exist (Abel et al. 2013, Abel 2016). Experiences with and research on the economic viability of the utilisation of wet peatlands are, however, still rare, but are a prerequisite for large-scale implementation since land users adopt sustainable practices only "if they are practical and financially viable" (Rawlins & Morris 2010).

This doctoral thesis addresses the lack of knowledge on land use options for wet peatlands, especially on costs and benefits at the farm level. The economics of paludiculture is an emerging research field that is so far restricted by the lack of large-scale implementation and long-term practical experience. Two research areas appeared, however, suitable for economic studies: a) traditional wet peatland use options, including large-scale conservation management, and b) new paludiculture pilot sites. Accordingly, I selected the two most promising and currently most advanced paludicultural practices on fen and bog peatlands, respectively; in Europe:

a) Harvesting natural reed beds (**Paper I, II, III**)

b) Cultivating *Sphagnum* mosses (**Paper IV, V**).

At this stage, research can hardly build up on established procedures or standard cost data but needs to follow explorative approaches. To answer the overarching question "Can paludiculture be an economic alternative to drainage-based peatland use at farm level?" this thesis focused on the following issues:

1) Practical feasibility: What procedures, methods and techniques are required to implement reed and *Sphagnum* paludiculture?

2) Profitability: What costs and benefits occur? How can economic viability be assessed?

3) Market prospects: What are the prospects of the biomass produced for different utilisation avenues? What area potential for paludiculture can be derived from the market demand?

4) Framework conditions: What further aspects affect decisions on peatland utilisation?

Chapter 2 explains data collection and the methodological approaches applied to explore the economics of paludiculture. The results for fen paludiculture (reed) are presented in **Chapter 3** and for bog paludiculture (*Sphagnum*) in **Chapter 4**, – both chapters address the specific procedures, costs, profitability, market prospects and area potential. **Chapter 5** looks beyond the determinants at the farm level and discusses how legal and policy regulations affect the profitability and feasibility of paludiculture. **Chapter 6** provides an outlook on research needs and next steps for implementing paludiculture.

2 Materials, methods and study areas

2.1 The triangulation of data sources and methods

This thesis adds to the field of problem-driven interdisciplinary 'sustainability science' (Kates et al. 2001) and its central component 'land-use science', which studies land use (change) at the interface of social systems and ecosystems and its implications for the global environment (Müller & Munroe 2014). Exploring the economic feasibility of paludiculture required an interdisciplinary approach, combining quantitative and qualitative methods from economics, social sciences and ecology (Table 1).

Table 1: Methods applied to study the four aspects of economic feasibility of reed and *Sphagnum* paludiculture

	Reed	Paper	*Sphagnum*	Paper
Peatland type **Management intensity** **Biomass utilisation**	– Fen – Low-input: harvesting established stands – Thatching, combustion, biogas generation		– Bog – High-input: rewetting and stand establishment – Founder material, orchid cultivation, peat substitute	
1) Practical feasibility	– Study area: winter and summer harvest of reed stands in Germany, Netherlands, Poland, Austria	**I**	– Study area: pilot trials on former bog grassland, cut-over bog, artificial water bodies in Germany	**IV, V**
2) Profitability	– Field measurements, semi-structured expert interviews, standardised questionnaire, literature review – Cost-revenue-calculations – Stochastic scenario analysis	**I**	– Field measurements (biomass production, bulk density, time requirements), expert interviews – Investment appraisal – Sensitivity analysis (low / medium / high values)	**IV, V**
3) Market prospects and area potential	– Semi-structured questionnaire, literature review, trade statistics (Europe) – Survey among thatchers, (structured questionnaire, Northern Germany)	**II** **III**	– Literature review (focus on Europe and Germany)	**V**
4) Framework conditions	– Document analysis, literature review – Expert interviews	**I, III**	– Document analysis, literature review – Expert interviews	**V**

Procedures and costs of paludiculture were studied in transdisciplinary research projects in close cooperation with practitioners. The case of reed represents traditional 'low-input' paludiculture, i. e. the utilisation of existing 'wild' vegetation stands. The case of *Sphagnum* represents novel 'high-input' paludiculture including construction works, stand establishment and water management required for the active transformation from drainage-based peatland use to paludiculture. For both produces, I investigated three different biomass utilisation avenues, using a variety of data sources and methods: pilot trials, field measurements, semi-structured expert interviews, structured questionnaires as well as secondary data from trade statistics and literature. Data analysis for profitability assessment included extended contribution margin calculations (reed) and investment appraisals (*Sphagnum*). I conducted stochastic scenario analysis (reed) and sensitivity analysis (*Sphagnum*) to account for the range of data values and uncertainty related to costs, yields and revenues. The geographic focus was primarily on Northern Germany (e. g. Sphagnum farming trials in Lower Saxony, survey among reed thatchers). I also addressed the European level (e. g. practical experiences with harvesting reed in other countries, European Union Common Agricultural Policy) as well as the global trade of reed and *Sphagnum*. From the novelty of the topic follows a lack of information, perspectives and data for comparing and validating the own research results. Therefore, this thesis puts special emphasis on the triangulation of data sources, methods for data collection and methods for data analysis.

2.2 Harvesting reeds

Common reed (*Phragmites australis*) is a tall, thin, highly productive grass that can be found in wetlands all around the world and has a long history as a plant used by humans (Haslam 2010). The wide range of applications encompasses fodder, litter, construction, insulation, pulp and paper as well as energy generation (Rodewald-Rudescu 1974, Wichtmann 1999, Haslam 2010, Köbbing et al. 2013). The Marsh Arabs in Southern Iraq are famous for their culture based on reed (Thesiger 2007, first published 1964). In Europe, the utilisation as a roofing material, i. e. for thatching, is the best known and most common application.

For common reed, I investigated the harvest of established vegetation stands and compared three options of biomass utilisation: a) biogas production, b) direct combustion and c) thatching (**Paper I**). The stage of implementation ranged from pioneering commercial plants (use as bioenergy feedstock) to an established international market (thatching material). In-depth, semi-structured interviews were conducted with reed cutters and landscape managers with extensive (20–30 years) experience in wetland-adapted machinery, site productivity and revenues in four countries in Central Europe (Germany, Netherlands, Poland, Austria; n=10). A standardised questionnaire sent to all biogas plants in Northeast Germany (N=237, 19 % response rate) investigated the use of grass-like biomass and the willingness to accept biomass from paludiculture. Field work included the measurement of working time and acreage performance during summer and winter harvest using GPS tracking (logger Wintec WBT-202). Values for biomass productivity, revenues and harvesting performance were compared with and complemented by literature data.

The profitability assessment for reed harvesting (**Paper I**) was based on an extended contribution margin accounting reflecting that revenues must cover not only variable costs (labour, fuel, machine care) but also fixed costs of specialised single-purpose machinery (e. g. deprecation, insurance). To account for uncertainty and ranges of data, I performed stochastic scenario analysis using Monte-Carlo simulations. Each input variable of the calculation model was given a range of values and a probability distribution. Interdependencies between single variables were considered by using positive and negative correlation factors, e. g. between biomass yield and harvesting effort. The software @risk 6 (Palisade Corporation) was used as an add-in for spreadsheet software (Microsoft® Office Excel 2013) to generate a large number of iterations (n=10,000) for each harvesting regime. Stochastic sensitivity analysis by Spearman's rank correlation identified the input variables with the highest influence on the output values 'harvesting costs' and 'contribution margin'.

Since reed for thatching is the most profitable of the investigated utilisation options (**Paper I**) and reed bundles are a globally traded commodity, I assessed the market situation in Europe and Germany. To provide a comprehensive picture of the European thatching reed market (**Paper II**), I applied a triangulation of methods: First, a semi-structured questionnaire answered by different reed experts (n=14; reed producers, traders, thatchers and representatives of umbrella organisations) allowed to elicit information on prices and personal insights in changing national demand. Second, analysing EU trade statistics delivered objective data on volumes exported or imported and their change over time. Third, extensive literature research collated widely scattered data and was especially valuable for cross-checking information originating from different periods. To get a detailed picture of the thatching reed market and the market potential for reed of regional origin (**Paper III**), we chose Northern Germany as study area. In this region, traditional reed cutting is maintained at a small-scale and reed thatched houses are common near the coasts of the North Sea and the Baltic as well as in areas rich in inland water. We focused our study on thatching companies being the key actors in the value chain by linking the final demand with the market for raw materials. All identifiable companies were provided with a combined mail and internet questionnaire using the web-based software tool EvaSys (N=141, response rate: 33 %). Extrapolating the survey data at a 95 % confidence interval allowed to estimate the total market volume of reed for thatching in bundles and monetary values, the market volume and market potential for reed of regional origin and the respective potential for cultivating reed for thatching in paludiculture.

2.3 Cultivating *Sphagnum* mosses

Biomass from *Sphagnum* species has been traditionally gathered locally for a wide range of applications and is nowadays mainly used for orchid cultivation (**Paper V**). The commercial collection from wild *Sphagnum* populations takes place in countries with extensive peatlands (e. g. Finland, Reinikainen et al. 2012) or *Sphagnum*-dominated (secondary) wetlands ('pomponales' in Chile, Díaz et al. 2008, Domingues 2014). 'Sphagnum farming' was initially considered as a means to provide *Sphagnum* biomass as an 'inoculum' for peatland restoration (Money 1994), but has been progressed as a new agricultural crop, especially to produce a renewable substitute for slightly decomposed 'white peat' in horticulture (Gaudig et al. 2018).

Pilot trials have demonstrated the practical feasibility of establishing *Sphagnum* cultures on former bog grassland, cut-over bogs and mats floating on acidic waters bodies resulting from peat, sand or lignite mining. I conducted a first assessment of the cost of establishing commercial *Sphagnum* cultures at these three site types and compared the relevant establishment procedure (**Paper IV)**. In a first qualitative step, I defined how *Sphagnum* cultures are established and which costs must be considered based on the experience of pilot trials in four German research projects (2004–2015). The second, quantitative step determined costs and time requirements based on real-life data from pilot trials, long-term experience of preparing cut-over sites for rewetting and restoration and information on costs provided by enterprises involved in the projects. I conducted dynamic investment calculations and tested the effect of different total cultivation times (5, 10, 20 years) and interest rates (3 %, 5 %) on the annuity of the initial establishment costs and related costs of the harvested yields.

Former bog grassland appeared to have the highest area potential for commercial Sphagnum farming in Germany (**Paper IV**). Therefore, this land category was chosen to conduct further economic studies based on real-life data and a first profitability assessment, using the pilot site Hankhausen near Rastede in Lower Saxony, Northwest Germany (53° 15.80' N, 08° 16.05' E) (**Paper V**). The main land use in that study area is drained bog grassland used for dairy farming and, to a lesser extent, suckler cow husbandry. The field trial was established in 2011 on a 4 ha site with a net area of 2 ha of *Sphagnum* production fields, the remaining area being occupied by causeways and ditches. In 2016, the first harvest provided *Sphagnum* shoots as founder material for the extension of the Sphagnum farming trial to about 14 ha (net: 5.6 ha).

The data from the first five years, including one full rotation cycle with site establishment, management and harvest, were used to calculate costs and revenues for a cultivation time of 20 years with four harvests. Costs and revenues are spread irregularly over the total cultivation time, as is common for permanent cultures. Sphagnum farming requires a high one-off investment for establishment at the start. Management costs occur every year. Costs for harvesting, transport and processing as well as market revenues arise every five years. Therefore, I conducted an investment appraisal discounting all cash flows of costs and revenues to a Present Value. I conducted a sensitivity analysis for the costs (high and medium cost level for establishment and management) and yields (productivity, bulk density) based on the real-life data from the Sphagnum fields. For the revenues I calculated low, mean and high price levels linked to three different utilisation avenues: a) high-quality alternative to white peat in horticultural growing media, b) raw material for orchid cultivation and c) founder material for Sphagnum farming or bog restoration. In addition, the effect of annual public non-market payments on profitability and break-even price was tested. Furthermore, the prospects of *Sphagnum* biomass for different 'niche markets' and as a renewable substitute for peat in horticulture were assessed in **Paper V**.

3 Paludiculture on fens: harvesting reeds

3.1 Harvesting procedures for reed-dominated vegetation stands

An economic summer harvest of fen species like common reed (*Phragmites australis*) and sedges (*Carex* spp.) requires machines adapted to water-saturated soil. Special machinery is also needed for winter harvest since long and strong enough frost periods do not occur every year in Central Europe. 'Seiga' machines, equipped with balloon tyres, have been used to harvest thatching reed since the 1950s. Modified snow groomers and newly developed special-purpose tracked machinery are increasingly used for biomass harvest, including the large-scale conservation management of fens. This special machinery is characterised by a low ground pressure as well as specific harvesting devices adapted to the intended utilisation avenue for the biomass (**Paper I**).

The summer-harvested green chopped biomass (chaff) can be processed in a dedicated biogas plant to generate gas for power and heat. Cutting and windrowing are conducted with a rotary mower or cutter bar in one pass, and the swath is picked up by a forage wagon or gathered by a chopper and placed into a trailer. Funds for conservation management to maintain habitats of target species or remove nutrients initiated the development of efficient mowing machines adapted to wet peatlands; biomass processing is, however, rarely established. The high costs of transporting fresh biomass with a high water content restrict processing to local markets. Biogas generation seems to be suitable since biogas plants are widely established, but a survey among biogas producers conducted in 2012 revealed a low acceptance of fen biomass (**Paper I**).

Biomass for direct combustion is harvested on dry winter days when its moisture content is sufficiently low to cut and press the reed into round bales in a single pass. A separate vehicle equipped with a crane picks up the bales and transports them to the edge of the field. Although specialised machines for harvesting bales have been tested in pilot trials in Austria and were further developed in recent years by Dutch and German companies, mature machinery is still lacking. In contrast, winter harvested reed biomass is well suited for combustion in state-of-the-art furnaces designed for materials such as straw or Miscanthus. Harvest for direct combustion enables the utilisation of sites that do not meet the quality demand of thatching reed, including heterogenous or old vegetation stands (**Paper I**).

High-quality thatching reed is harvested in winter when the leaves have fallen and moisture content is low. In one pass, the long, straight culms are mown with a cutter bar, brushed for initial cleaning and bound into bundles with a circumference of approximately 65–70 cm. A separate vehicle transports large bales of several hundred bundles to the edge of the field. After further drying, every single bundle is opened, cleaned and bound into tight bundles (55–60 cm circumference) ready for sale and thatching (**Paper I**). Reed for thatching is the most established option with mature harvesting technology, sophisticated high-value application and a commodity traded on the global market.

3.2 Profitability of harvesting reeds for biogas production, direct combustion and thatching

Cost accounting clearly showed that there is not one valid answer whether paludiculture is profitable. With current knowledge and limited experience, single point estimates of profitability are easily miscalculated. Monte Carlo simulation provided a more accurate picture of reality by showing the possible range of loss or profit and the risk of loss (**Fig. 1**). In addition, the maximum of the probability density function (mode) can be used as robust point value. Over all three harvesting regimes, the income left after subtracting variable costs and fixed machinery costs (defined as contribution margin II) ranged from ca. € – 1000 to € 1500 ha^{-1} a^{-1} (**Paper I**).

Harvesting chaff for biogas production is not profitable (range: € – 1036 to € 179 ha^{-1} a^{-1}, mode: € – 195, risk of loss: 98 %) (**Paper I**), because wetland biomass is low in demand for anaerobic digestion and the price consequently similarly low. Digestibility and methane yield are lower compared to standard substrates as maize silage. Furthermore, most of the existing plants (53 %) were not adapted to process grass-like biomass. Agricultural subsidies for wet grassland and agri-environmental payments are needed to cover harvesting costs and allow summer harvest to be an established practice – but usually without commercial use of the biomass.

Direct combustion of winter harvested bales may cover harvesting costs (range: € – 287 to € 677 ha^{-1} a^{-1}, mode: € 53, risk of loss: 18 %), except when several influential input variables have pessimistic values such as a low revenue level and a low acreage performance of mowing and baling (**Paper I**). The economic viability depends especially on the regional price for straw, that competes with reed, the distance to the combustion plant and legal and policy regulations, which currently disadvantage the winter harvest of reed compared to summer harvest.

Harvesting bundles for thatching is the most profitable option and the probability of a loss was near zero (range: € – 162 to € 1542 ha^{-1} a^{-1}, mode: € 572, risk of loss: <1 %). Its high revenue favours harvesting reed for thatching rather than for combustion or biogas production despite having the highest harvesting costs (**Paper I**). In Germany, this most profitable utilisation avenue suffers from the loss of wetland area during the 20th century, nature conservation law restricting reed harvest both in space and time, the restricted availability of high-quality reed, as well as by thatch not being considered an agricultural product and consequently not being eligible for agricultural subsidies (**Paper I, Paper III**).

Next to biomass yield and price, which strongly influence profitability, the acreage performance of harvesting and transporting machinery plays a decisive role in all production regimes. Improved technology and logistics, increased capacity utilisation of machinery and economy-of-scale effects are expected to reduce costs compared to currently used immature prototypes or modified second-hand snow-groomers. In addition, acreage performance depends greatly on the specific site conditions like soil trafficability, uneven surface, amount of shrubs, field sizes and access points (**Paper I**). Transforming agriculturally used peatlands into paludiculture sites taking into account the special requirements of biomass harvest and logistics (cf. Schröder et al. 2015) will very likely improve acreage performance compared to the study sites.

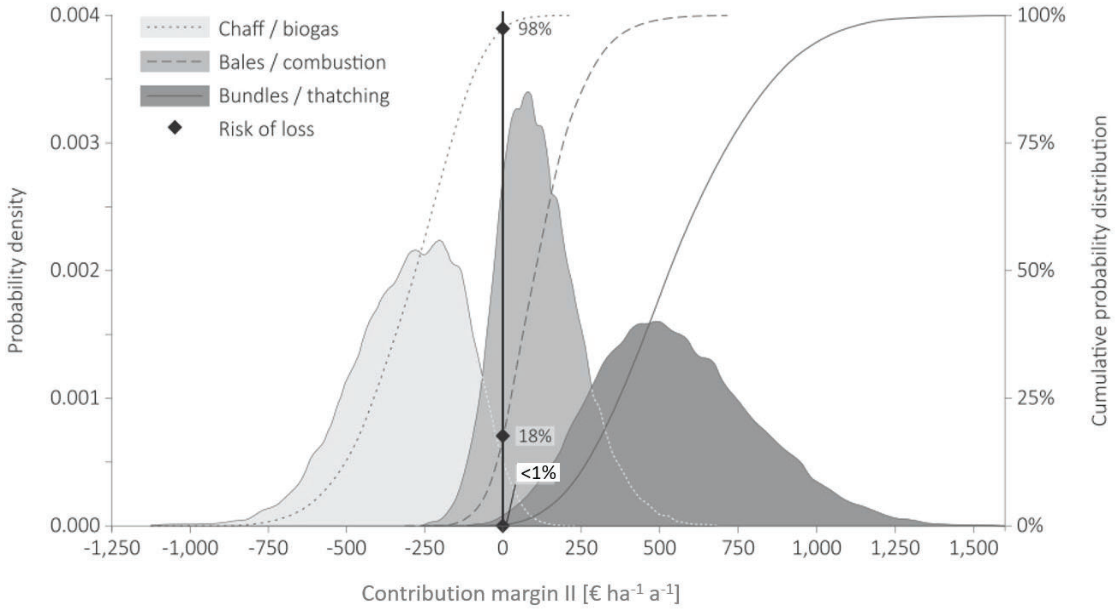

Figure 1: Results of the Monte-Carlo simulation for three variants of reed biomass supply for material and energy use. The grey curves represent the results of the contribution margin accounting (number of iterations: 10,000). The cumulative distribution function reflects the probability that the result takes a value of x or less, implying in the case of x < 0 a risk of loss. (Wichmann 2016, after **Paper I)**

3.3 The European market of thatching reed

Until today, thatching is the best known and most common application of reed in Europe with reed roofs having a landscape defining character, especially in many coastal regions. Every landscape has a traditional regional building and thatching culture with specific house types, roof shapes, or materials used for the roof ridge. Today, reed is also used for new applications in modern architecture, for instance also for thatching walls (**Paper III**). Despite its long tradition as locally available, cheap thatching material, reed thatch is nowadays an internationally traded commodity.

A first review of the European market (**Paper II**), analysing total consumption, imports and exports since 1990, revealed a discrepancy between consuming and producing countries. Major reed consuming countries in Western Europe, mainly Germany, the Netherlands, the United Kingdom and Denmark, rely for up to 85 % on imports to meet the national consumption. Exporting countries were mainly located in Southern and Eastern Europe, especially Romania, Ukraine, Hungary, Poland, Austria and Turkey. High dynamics in the amounts of reed traded among countries were observed. Since 2005, reed from China accounts for a considerable share of the European market with exports mainly to the Netherlands. Many other European countries are known to have reed thatching traditions, but exports or imports are of less importance for the international market, e. g. Belgium, Ireland, Luxembourg, Italy, France, Lithuania, Latvia, Estonia, Sweden and Finland. The total demand of the European market has increased since 1990 and currently amounts to approximately 15 million bundles per year. All stakeholders involved in the reed business expressed strong concern that the domestic supply will further decline and the dependence on imports will increase. The shortage of reed leads to the trade of bad quality material, which likely contributes to the early or premature decay of single thatched roofs (**Paper II**).

3.4 Market prospects of domestic reed in Germany

Germany has a long and living tradition in reed thatching. The German UNESCO commission included the thatcher's craft in the Inventory of Intangible Cultural Heritage. The first in-depth analysis of the market for thatching reed (**Paper III**) revealed for Northern Germany 141 companies working with reed as thatching material and 62 % of the responding companies being specialised in using reed as the only roofing material. Less than 9 % of the responding companies harvested reed, and another 26 % had given up reed cutting during the last decades. In the year 2018, reed from Germany held a low share of 17 % of the total consumption. If we include reed from the neighbouring Polish part of Pomerania, about 20 % can be considered as 'regional'. The share of the reed imported from China was 16 %. Other important reed producing countries exporting to Germany hold a share of 63 % of the reed used in 2018 (**Paper III**). The majority of reed (59 %) was used for rethatching existing buildings completely, 24 % for newly constructed roofs and 17 % for roof repairs (**Paper III**).

All thatchers (100 %) stated that the quality of reed, as for instance cleanliness (91 %) and culm length (87 %), is an important purchasing criterion. The origin of the reed was a relevant criterion for 54 % of the respondents and the price was mentioned only by one third (**Paper III**). Regional reed was generally judged to be equal in quality compared to other origins (mean: 3,97, Likert scale 1-7). All those thatching companies engaged in harvesting reed, however, considered regional reed of superior quality. The majority of the thatchers (70 % of respondents) do not promote reed of regional origin to their customers due to insufficient supply as the first (50 %) and poor quality, e. g. regional reed being too short or too soft, as a second reason (31 %). The majority (69 %) of these thatchers, not yet promoting domestic reed, would be willing to offer the utilisation of reed of regional origin to their customers and 86°% of the thatchers already promoting domestic reed would be willing to offer more (**Paper III**).

The survey results for the year 2018 were extrapolated to the entire thatching market in Northern Germany. We estimated a total market volume of 3 ± 0.8 million bundles and a market value at sales prices of € 11.6 ± 2.8 million. The current market volume of domestic reed is estimated at 0.5 million bundles. Based on the share of costumers asking explicitly for regional reed, more than double the number of bundles of regional origin could have been sold, resulting in a market potential for domestic reed of 1,034,000 ± 367,000 bundles and a market value of € 3.7 ± 1.3 million (**Paper III**).

3.5 Potential area demand for cultivating reed

From the market studies (**Paper II, III**), it can be concluded that a demand exists for more and above all more high-quality thatching reed of regional origin. Cultivating reed in paludiculture may improve both quantity and quality of regional reed as a traditional ecological roofing material. The cultivation of reed may range from shifting the harvest season from summer to winter, over improved water management, the planting of pre-cultivated seedlings for stand establishment, up to the selection of provenances, genotypes, or even breeding for improved reed quality (**Paper III**). Several pilot trials proved the feasibility of planting reed for establishing reed stands and practical experience with the commercial harvest of planted reed stands is available. Research on how to achieve and improve thatching qualities of reed cultivated on rewetted peatlands is in progress. The identified supply gap can be filled by an additional harvest area of about 1000 ha. If we consider that 70 % of the responding thatchers do not yet promote reed of regional origin to their customers, the potential can be larger than calculated. In terms of area demand, 6000 ± 1600 ha with an average yield of 500 bundles per hectare would be sufficient to produce all 3 million bundles of the current total German market (**Paper III**). To be on the safe side, e. g. to accommodate for harvest failures, an area of 10,000 ha would be more than sufficient.

4 Paludiculture on bogs: Sphagnum farming

4.1 Procedures of Sphagnum farming

To ensure high *Sphagnum* productivity in Sphagnum farming, site selection, planning, establishment and management must focus on an optimal water supply avoiding both drought and flooding as well as on suitable soil and water quality. Soil-based *Sphagnum* cultures on degraded bogs require a site preparation that includes the provision of an even surface, the installation of infrastructure for water management (pump, inflow, irrigation ditches or pipes, outflow) and causeways as management and harvesting infrastructure (**Paper IV**, cf. Gaudig et al. 2018). In the test site Hankhausen on former bog grassland, the degraded, nutrient rich and limed top soil was removed (30 – 50 cm) and *Sphagnum* fragments were spread onto the bare peat surface using an adapted snow-groomer with a mounted manure spreader. Management included the site maintenance, i. e. regular weed mowing, cleaning of irrigation ditches, mulching of causeways, and the electronically controlled automatic water management. Harvest took place with an excavator standing on the causeway and equipped with long arm and mowing bucket, loading the biomass into a tractor pulled dumper. Biomass was processed (drying, cleaning, screening) by standard equipment in a commercial growing media plant.

Water-based *Sphagnum* cultures on acidic water bodies have the advantage of a permanent water supply. The intention is to imitate floating rafts in flooded peat pits known to support high *Sphagnum* productivity (Money 1994, Joosten 1995). Cultivation on water required the production of floatable mats (panels of polystyrene foam) ensuring permanent buoyancy as well as a constant supply of water to the mosses (via a polypropylene fleece) (**Paper IV**). *Sphagnum* fragments were stitched onto a carrying material and these pre-fabricated *Sphagnum* mats were rolled out on the floating mat, either directly after manufacture or after a period of soil-based pre-cultivation under sheltered conditions. Installation, but also the management and harvesting of the mats require more effort (e. g. time and work safety) than soil-based work. Further challenges include damage by wind, waves, ice-drift as well as waterfowl using the mats for roosting and nesting. Fluctuating water levels caused problems on shallowly flooded cut-over bogs (**Paper IV**).

4.2 Comparison of establishment costs of water- and soil-based *Sphagnum* cultures

Compared to soil-based *Sphagnum* cultures, water-based cultures had by far the highest establishment costs per net production area encompassing € 17.34 m^{-2} without and € 21.34 m^{-2} with pre-cultivation of *Sphagnum* mats (**Paper IV**). The main factor was the high production costs of the pre-fabricated mats (54 and 63 % of the total costs). Furthermore, the durability of cultures on mats is insufficiently understood and disposal costs for the mats must be considered in addition to replacement costs. Water-based cultures very likely involve a shorter total cultivation time (9 – 10 years) and intermediate costs for re-establishing *Sphagnum* mats, which will increase the disadvantages of high initial costs. The total cultivation time strongly influenced the calculated annuities whereas altering the interest rate (3 %, 5 %) had limited effect.

For soil-based *Sphagnum* cultures, a longer total cultivation time (20 years) appears to be reasonable and the establishment costs were considerably lower (€ 8.35 m^{-2} to € 12.80 m^{-2}) (**Paper IV, Paper V**). The lowest costs relate to cut-over bog, mainly because the bare peat surface remaining after peat extraction reduces the effort for site preparation. The purchase of *Sphagnum* shoots (€ 750 m^{-3}) was most influential with 46 % of total establishment costs on former bog grassland and 71 % on cut-over bog (**Paper IV**). Cultivating own founder material on the pilot site on former bog grassland reduced its costs by 41 % (**Paper V**). The second most important cost element was the investment costs for the water management which may vary widely depending on the choice of the irrigation system (€ 1 to € 4.59 m^{-2}) (**Paper IV**). The high investment costs related to installing a power supply and an electronically controlled automatic water management system were proportionally reduced by half (€ 2.22 m^{-2}) once the infrastructure was used for a larger moss production area. Total establishment costs on former bog grassland could be investigated twice. I calculated costs of € 127,862 per hectare production field in 2011 and € 98,446 ha^{-1} in 2016. Less than € 50,000 ha^{-1}, i. e. € 5 m^{-2}, seems feasible based on current knowledge (**Paper V**).

4.3 Profitability of Sphagnum farming on former bog grassland

The pilot site on former bog grassland allowed the first cost and profitability assessment for large-scale, mechanically implemented Sphagnum farming (**Paper V**). Five years of real-life data – from the establishment to the first harvest – were analysed and extrapolated to a total cultivation time of 20 years. The investment appraisal, discounting all cash flows of costs and revenues to a Present Value, revealed that the total of annual management costs exceeded the high one-off establishment costs. The Present Value of the revenues ranged very widely from € 18,000 to € 2,312,000 ha^{-1} depending on yield and price of the various utilisation avenues. I found that *Sphagnum* biomass cultivated as raw material for horticultural growing media cannot compete with peat at its current market price (25 € m^{-3}), which excludes the external costs of peat extraction. Cultivating *Sphagnum* is economically viable for orchid cultivation (165 € m^{-3}) in the case of medium to high Sphagnum yields at low bulk density (**Fig. 2**). Selling Sphagnum shoots as founder or 'seeding' material is profitable even in the most pessimistic scenario with high costs, high bulk density and low yields. The break-even price with a maximum of € 423 m^{-3} lies well below the € 750 paid for the founder material for setting up the pilot trial.

	Low yield		Mean yield		High yield	
Productivity [t ha^{-1} a^{-1}]	**3.1**		**4.9**		**6.8**	
Harvested yield [t ha^{-1} a^{-1}]	**2.0**		**3.2**		**4.4**	
Bulk density [g L^{-1}]	38	20	38	20	38	20
"Seeding material"	✓	✓	✓	✓	✓	✓
Orchid cultivation	✗	✗	✗	✓	✗	✓
Peat substitute	✗	✗	✗	✗	✗	✗

Figure 2: Profitability of Sphagnum farming depending on yield (productivity, bulk density) and prices for various utilisation avenues: green checkmarks indicate profitable combinations, the red cross symbolises negative Net Present Values i. e. the Present Value of Revenues is lower than the Present Value of the Costs (after **Paper V**).

I identified a high potential for optimisation and cost reduction decreasing the calculated break-even price by 20 % in the medium cost scenario compared to the high cost scenario. Key factors for further cost reduction are minimising topsoil removal, a decreasing price of founder material (own production or mass propagation), cost-efficient infrastructure for water management, optimising weed management (e. g. machinery, frequency) and scale effects (**Paper V**). Revenues can be increased by increasing *Sphagnum* productivity through selecting high productive species, provenances and breeds (Gaudig et al. 2018). Addressing niche markets (e. g. founder material) and established high-value markets (e. g. orchid production) with higher prices most feasibly covers the high production costs of Sphagnum farming at the pioneering stage. An assumed non-market income of € 1300 ha^{-1}, i. e. eligibility for agricultural direct payments and the remuneration of external benefits, decreased the break-even price slightly by 6 %. The largest effect was identified for the prices paid for the horticultural end products. If end consumers pay a surcharge of 10 % for peat free cultivated plants, cost-covering prices for *Sphagnum* biomass substituting peat seem achievable already today (**Paper V)**.

4.4 Market prospects of *Sphagnum* biomass

The price for the produced *Sphagnum* biomass has, not surprisingly, the highest effect on profitability as especially shown for founder material for Sphagnum farming and bog restoration relying on regional provenances (**Paper V**). Other high-value 'niche market' applications ensuring high revenues encompass substrates for carnivorous plants, for vivaria with amphibians, reptiles and spiders, or for hanging baskets, wreathes and vegetation walls. Using *Sphagnum* material as insulation and packaging material, for food preservation, medical dressings, nappies and sanitary towels are among traditional as well as current applications. New utilisation options will likely develop based on newly emerging biological properties and compounds, such as *Sphagnum* extracts as sources of natural sunscreen (**Paper V**). A recent study characterises *Sphagnum* moss as an ideal novel growth medium for indoor agriculture which is considered important to ensure future global food security (McKeon-Bennett & Hodkinson 2021).

The main reason for *Sphagnum* biomass being collected in wild populations and globally traded as a high-value commodity with the image of 'Green Gold' is its application in the orchid sector (**Paper V**). In China, *Sphagnum* is cultivated on mineral soils as a high-value product for orchid production resulting in individual incomes that are about eight times higher than rice cultivation in the same area (Ludwig 2019). Europe plays a minor role in the worldwide *Sphagnum* market (**Paper V**). To produce the total quantity of 9,000 m^{-3} of *Sphagnum* imported to The Netherlands, France and Germany in 2013 would require 41 to 167 ha of *Sphagnum* production fields with high to low yields (**Paper V**). While high-value applications are important to start up commercial Sphagnum farming, addressing larger markets is necessary to establish Sphagnum farming as a sustainable, climate-smart alternative to predominant drainage-based bog grassland farming in NW Germany **(Paper V**).

Sphagnum biomass is a high-value constituent of growing media having similar properties as slightly humified *Sphagnum* peat ('white peat'). *Sphagnum* biomass has been successfully used in potting substrates for a wide range of horticultural applications with shares up to 100 %. In contrast, other renewable raw materials for growing media such as green-waste compost, composted bark and wood fibre have limited qualitative suitability to fulfil professional demands and their application rates remain low. The total volume of growing media used in Europe amounts to 35 million m^3 with Germany being the most important producer country responsible for a share of 24 % (8.4 million m^3) (**Paper V**). Germany's growing media industry has an annual demand of ~3.5 million m^3 of 'white peat' (**Paper IV**) and of ~3.2 million to 6 million m^3 of highly decomposed 'black peat' (**Paper V**). The German climate protection program (BMU 2019) includes a peat reduction strategy that shall lead to near-total elimination of peat in the hobby sector within 6 – 8 years and a far-reaching replacement in professional horticulture within a decade. In terms of quality, *Sphagnum* biomass can contribute considerably to reaching these ambitious goals; the current availability is, however, marginal due to the small cultivation area.

4.5 Potential production areas for Sphagnum farming in Germany

For all three types of *Sphagnum* culture, i. e. on bog grassland, cut-over bog or acidic water bodies, the potential production areas in Germany were assessed (**Paper IV**). About 70 % of Germany's remaining bog area is in Lower Saxony. Grassland is the dominant land use on bogs encompassing 90,000 ha, thus constituting the largest area potential for Sphagnum farming. About 30,000 ha of the bog area is allocated to peat extraction of which the majority will be rewetted for restoration by 2040 and only for about 500 ha of the ongoing peat extraction area an agricultural after-use is intended. In the case of acidic artificial water bodies, by far the largest area is provided by lakes resulting from opencast lignite mines, but for various reasons only a quarter, at maximum, seems appropriate for Sphagnum farming, i. e. about 10,000 ha. Considering the very high establishment costs for water-based culture and the small area potential of cut-over bogs, Sphagnum farming on former bog grassland offers the highest theoretical potential in Germany. A net moss production area comprising 35,000 ha of the 90,000 ha of bog grassland in Lower Saxony could produce sufficient *Sphagnum* biomass to completely replace the current 'white peat' requirement of the German growing media industry (**Paper IV**). However, the framework conditions, especially current legal and policy regulations, hamper the shift from drainage-based peatland use to sustainable Sphagnum farming.

5 Framework conditions affecting feasibility of paludiculture

The relation of revenues from selling biomass to its production costs is an important piece of the paludiculture feasibility puzzle. However, framework conditions ultimately determine whether a balanced provision of ecosystem services is hindered or encouraged in peatlands used for agriculture. Legal or policy regulations and the potential remuneration of external benefits have a decisive influence on the profitability and feasibility of paludiculture (**Paper I**).

Most contexts currently support the continuation of conventional agriculture, despite increased awareness of drained peatland dis-services. A lack of policy coherence is observed, especially ignoring climate policies when planning land-use or agricultural policies (**Paper I**). Throughout the EU, the Common Agricultural Policy (CAP) strongly influences peatland use by supporting continued drainage-based agriculture, e. g. via direct payments (Pillar I) but also agri-environment measures (pillar II), which most often do not prescribe raised water levels (Wichmann 2018, **Paper V**). The current CAP increases the profitability of drainage-based agriculture artificially since the public payments make up a considerable share of the income, e. g. for dairy farming on drained bog grassland in NW Germany (**Paper I, V**). In contrast, winter harvested reed stands in Germany are not eligible for direct payments. The classification of reed thatch as non-agricultural product causes not only unequal economic conditions, but also limits the area of land available for reed cutting. Despite lacking biomass utilisation, land managers prefer to mow wet grassland in summer to receive EU subsidies and thus impede a winter harvest for thatching (**Paper III**). The European Court of Auditors (2021) criticised the CAP for attributing € 100 billion of funds to climate action without achieving significant mitigation effects (2014 – 2020) and for supporting farmers for cultivating drained peatlands, which emit 20 % of EU-27 agricultural GHG. The negotiations on the new CAP failed, however, to initiate the necessary transition at the European level. The support of peatland drainage and discrimination of paludiculture will most likely continue for another decade. However, member states may integrate incentives for rewetting and paludiculture in their national strategic plans and thus stimulate implementation as was shown by Polish agri-environmental payments, which initiated the management of wet fen peatlands on over 10,000 ha (**Paper I**). Cost data elaborated in this thesis may inform policy makers for determining payment heights e. g. to support investment in peatland rewetting and establishing paludicultures, purchasing special-purpose harvesting machines, ensuring high water levels and harvesting of biomass from wet peatlands.

Apart from agricultural payments, legal regulations on the general protection of permanent grassland and nature conservation law affect the implementation of paludiculture. European and regional regulations limit the transformation of grassland into permanent cultures, e. g. with *Sphagnum* mosses and common reed, thereby ignoring that organic and mineral soils require different measures for soil carbon protection (GMC & DVL 2021) as well as the proven value of paludicultures as habitat for endangered peatland species (e. g. Muster et al. 2015, 2020, Tanneberger et al. 2009).

As long as drainage-based peatland farming is not restricted by regulatory law and spatial planning, its opportunity cost impacts the commercial viability of paludiculture; the profit to overcome usually increases with the intensity of current land use and varies greatly among countries and regions (**Paper I**, Buschmann et al. 2020). For Germany, peatland restoration was identified as the most cost-efficient land use based greenhouse gas abatement measure, especially in NE Germany (Röder et al. 2015). So far, socio-economic studies on peatland rewetting have been assuming either the abandonment of productive use in case of water levels near the surface (e. g. Röder et al. 2015) or an adaptation to moderately higher water levels, including declining suitability of the biomass for conventional farming and decreasing market revenues (Schaller 2014, Krimly et al. 2016). Studies on an active transition to paludiculture with new approaches and farming perspectives are largely lacking. Changing conditions, such as higher production costs in peatlands due to rising water tables, increasing energy prices, and technical progress in processing biomass, will favour for instance future reed cultivation in contexts in which it currently cannot compete with conventional agriculture (**Paper I**).

From the societal perspective, stopping drainage and raising peatland water levels to the surface is indispensable to contribute to climate protection. To avoid disruptive changes in peatland-rich regions, it is crucial to clearly communicate this far-reaching objective, to develop a new perception of peatlands acknowledging their multiple benefits and to plan the long-term transition. Creating new 'wet wilderness' according to the 'land sparing' concept, i. e. the spatial segregation of agricultural areas and natural areas, enhances biodiversity and may initiate the development of new income opportunities based on environmental education and eco-tourism. The 'land sharing' concept integrates productive use and conservation on the same area of land and ideally considers bundles of ecosystem services (Grau et al. 2013) as it is inherent to paludiculture. Reasons for favouring paludiculture over abandonment after peatland rewetting may include a higher local acceptance for productive use, the demand for crops with specific biomass properties, an increasing demand for renewable raw material and energy and specific management needs to meet nature conservation targets.

Changing the framework is an essential strategy to move paludiculture as a sustainability innovation from its current classification as a marginal phenomenon to a transformational path (Ziegler 2020). To align agricultural policy to climate policy, agricultural subsidies for drainage-based peatland use need to be phased out in a first step and in a second step higher water levels should be prescribed. To initiate the paradigm shift to climate-smart agriculture on peatlands, a set of attractive economic incentives will be necessary such as compensating for the high initial investment, facilitating large-scale implementation by supporting advice and cooperation, long-term schemes remunerating reduced GHG emissions as well as the provision of other ecosystem services and increasing market demand for climate-friendly products, e.g. via public procurement (**Paper V**).

6 Conclusion and Outlook

The high expectations for paludiculture at the policy level contrasts with the lack of knowledge on practical feasibility and economic viability as well as with the detrimental policy and legal regulations hampering its implementation. While peatland drainage and reclamation have been elaborated over centuries, we face the need for fast action and result delivery to meet the challenge of transforming peatland management within the next three decades.

This thesis provides the first assessment of the costs of large-scale harvesting of reeds and Sphagnum farming based on real-life data. In particular, it calculates the profitability of these two paludicultural practices in dependence of different biomass utilisation avenues, identifies optimisation potentials, analyses the market prospects and estimates the potential cultivation area in Germany. Common reed for thatching on fen sites and *Sphagnum* mosses on bog sites combine climate-responsible peatland management with the cultivation of high-value products. With a total of 383,000 ha of arable land and 852,000 ha of grassland on drained peatlands and other organic soils in Germany (**Paper III**), they may provide a solution for a share of less than 50,000 ha (**Paper III, IV**).

Other, additional biomass utilisation avenues and other crops need to be investigated to provide further economically viable paludicultural options (**Paper III**). Wet meadows developed by natural succession are a low input option, have the least conflict potential with nature conservation and therefore have the highest potential for large-scale implementation. As biomass utilisation for heat or power generation is so far less attractive (**Paper I**), the processing of heterogenous plant material to fibres suitable for producing paper, packaging, bioplastics, and boards for construction and insulation (Orozco et al. 2021) might be more promising. Cattail (*Typha* sp.) has specific structural biomass properties (aerenchyma) that make it most suitable for light, strong and well insulating construction material (Krus et al. 2013), but the cultivation is restricted to sites with a surplus of nutrients and water (Schätzl et al. 2006). Wetland species like reed canary grass (*Phalaris arundinacea*) may be used for phytomining based on their ability to take up and concentrate germanium and rare earth elements (Wiche & Heilmeier 2016). The specific 3D silicon structure in reed (*Phragmites australis*) leaves allows for very good electrochemical performance in Lithium-Ion Batteries (Liu et al. 2015), whereas sundew (*Drosera rotundifolia*, Baranyai & Joosten 2016) and herbs like meadowsweet (*Filipendula ulmaria*), hemp agrimony (*Eupatorium cannabinum*) and butterbur (*Petasites hybridus*) (Kersten et al. 1999, Abel et al. 2013) with medicinal effects may generate high-income at small scale, to name some examples.

To intensify research on the economics of paludiculture, large-scale pilot sites are required to allow for farm-scale implementation and to improve technical maturity of procedures and machinery. Thus, assumptions and ‘guestimates’ may be replaced by real-life cost data, and knowledge gaps, e. g. on productivity and harvested yields, may be overcome. Further experiences under different starting and site conditions can be gathered, potentials for optimisation and cutting costs identified and long-term effects studied (**Paper I, IV, V**). In addition, the micro-economic perspective needs to be complemented by the societal perspective assessing external effects of peatland restoration and paludiculture in comparison to drainage-based peatland agriculture and peat extraction. External effects may be monetised via a bonus (payments for ecosystem services) or malus system (e. g. CO_2 tax). Improving the “understanding of the linkage between changes in agricultural management and changes in resulting flows of ecosystem services is a key element of the research agenda on agriculture and ecosystem service valuation” (Swinton et al. 2007). Decision making on peatland use alternatives requires a complete picture of costs and benefits for the whole society, – the profitability at farm level being only one but a crucial part of it (**Paper V**).

The increased awareness of the multiple benefits provided by functioning peatland ecosystems turns rewetting into the new paradigm in peatland use (Convention on Wetlands 2021). Paludiculture is considered a key element supporting a just transition for local communities, land owners and farmers. In former times, large-scale and systematic peatland drainage took place because social elites and political authorities first investigated and incentivised, then prescribed and finally organised peatland reclamation – often in times of crisis and wars. Nowadays, it is the climate crisis that requires state action to initiate the transformation of peatland use via research, incentives, policy and legal regulations and large-scale publicly financed programmes for peatland rewetting.

References

Abel, S. (2016) Database of Potential Paludiculture Plants. In: Wichtmann, W., Schröder, C., Joosten, H. (eds.), Paludiculture - productive use of wet peatlands. Climate protection - biodiversity - regional economic benefits. Schweizerbart Science Publishers, Stuttgart, 21.

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.

Baranyai, B., Joosten, H. (2016) Biology, ecology, use, conservation and cultivation of round-leaved sundew (*Drosera rotundifolia* L.): a review. *Mires and Peat*, 18 (18), 1–28.

Barthelmes, A., Couwenberg, J., Risager, M., Tegetmeyer, C., Joosten, H. (2015) Peatlands and climate in a Ramsar context - A Nordic-Baltic perspective. TemaNord 2015:544. Nordic Council of Ministers, Copenhagen, 244 pp.

Biancalani, R., Avagyan, A. (eds.) (2014) Towards climate-responsible peatlands management. Food and Agriculture Organization of the United Nations (FAO), Rome, 100 pp.

BMU (Bundesministerium für Umwelt) (2019) Klimaschutzprogramm 2030 der Bundesregierung zur Umsetzung des Klimaschutzplans 2050, 173 pp.

Bonn, A., Allott, T., Evans, M., Joosten, H., Stoneman, R. (eds.) (2016) Peatland restoration and ecosystem services. Science, policy, and practice. Cambridge University Press, Cambridge. 493 pp.

Budiman, I., Bastoni, Sari, E.N.N., Hadi, E.E., Asmaliyah, Siahaan, H., Januar, R., Hapsari, R.D. (2020) Progress of paludiculture projects in supporting peatland ecosystem restoration in Indonesia. *Global Ecology and Conservation*, 23, e01084, 1–17.

Buschmann, C., Röder, N., Berglund, K., Berglund, Ö., Lærke, P.E., Maddison, M., Mander, Ü., Myllys, M., Osterburg, B., van den Akker, J.J. (2020) Perspectives on agriculturally used drained peat soils: Comparison of the socioeconomic and ecological business environments of six European regions. *Land Use Policy*, 90, 104181, 1–13.

Crump, J. (ed.) (2017) Smoke on water - countering global threats from peatland loss and degradation. A UNEP rapid response assessment., United Nations Environment Programme and GRID-Arendal, Nairobi and Arendal. 70 pp.

Convention on Wetlands (2021) Global guidelines for peatland rewetting and restoration. Ramsar Technical Report No. 11. Gland, Switzerland: Secretariat of the Convention on Wetlands. 77 pp.

Díaz, F., Larraín, J., Zegers, G., Tapia, C. (2008) Caracterización florística e hidrológica de turberas de la Isla Grande de Chiloé, Chile (Floristic and hydrological characterisation of Chiloé Island peatlands, Chile). *Revista Chilena de Historia Natural*, 81, 455–468.

Domínguez, E. (2014) Manual de buenas prácticas para el uso sostenido del musgo Sphagnum magellanicum en Magallanes, Chile (Manual of good practices for the sustainable use of Sphagnum magellanicum in Magallanes, Chile). Instituto de Investigaciones Agropecuarias, Centro Regional de Investigación Kampenaike (Institute of Agricultural Research (INIA), *Boletín INIA*, 276, 113 pp.

European Court of Auditors (2021) Common Agricultural Policy and climate: Half of EU climate spending but farm emissions are not decreasing. Special report, 16/2021, 64 pp.

Evans, C.D., Peacock, M., Baird, A.J., Artz, R.R.E., Burden, A., Callaghan, N., Chapman, P.J., Cooper, H.M., Coyle, M., Craig, E., Cumming, A., Dixon, S., Gauci, V., Grayson, R.P., Helfter, C., Heppell, C.M., Holden, J., Jones, D.L., Kaduk, J., Levy, P., Matthews, R., McNamara, N.P., Misselbrook, T., Oakley, S., Page, S.E., Rayment, M., Ridley, L.M., Stanley, K.M., Williamson, J.L., Worrall, F., Morrison, R. (2021) Overriding water table control on managed peatland greenhouse gas emissions. *Nature* 593, 548–552.

Gaudig, G., Prager, A., Wichmann, S., and 30 others (2018) Sphagnum farming from species selection to the production of growing media: a review. *Mires and Peat*, 20 (13), 1–30.

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. *Landbauforschung, Journal of Sustainable and Organic Agricultural Systems*, 69 (1), 5–8.

Giesen, W. (2021) Tropical peatland restoration in indonesia by replanting with useful indigenous peat swamp species: paludiculture. In: Osaki, M., Tsuji, N., Foead, N., Rieley, J. (eds.), Tropical peatland eco-management. Springer Singapore, Singapore, 411–441.

Glenk, K., Martin-Ortega, J. (2018) The economics of peatland restoration. *Journal of Environmental Economics and Policy*, 7, 345–362.

GMC, DVL (2021) Vorgaben zum Grünlanderhalt bei der Umstellung auf Paludikultur. Informationspapier. Greifswald Moor Centrum, Deutscher Verband für Landschaftspflege, Februar 2021. 9 pp. Online at: https://www.greifswaldmoor.de/files/dokumente/Infopapiere_Briefings/2021_GMC_DVL_Vorgaben%20zum%20Gr%C3%BCnlanderhalt%20bei%20der%20Umstellung%20auf%20Paludikultur.pdf

Grau, R., Kuemmerle, T., Macchi, L. (2013) Beyond 'land sparing versus land sharing': environmental heterogeneity, globalization and the balance between agricultural production and nature conservation. *Current Opinion in Environmental Sustainability*, 5, 477–483.

Haslam, S.M. (2010) A book of reed (*Phragmites australis* (Cav.) Trin. ex Steudel, *Phragmites communis* Trin.). Forrest text, Cardigan, 261 pp.

Hirschelmann, S., Tanneberger, F., Wichmann, S., Reichelt, F., Hohlbein, M., Couwenberg, C., Busse, S., Schröder, C., Nordt, A. (2020) Moore in Mecklenburg-Vorpommern im Kontext nationaler und internationaler Klimaschutzziele - Zustand und Entwicklungspotenzial – Faktensammlung. Proceedings of the Greifswald Mire Centre 01/2020 (self-published, ISSN 2627-910X), 33 pp.

Humpenöder, F., Karstens, K., Lotze-Campen, H., Leifeld, J., Menichetti, L., Barthelmes, A., Popp, A. (2020) Peatland protection and restoration are key for climate change mitigation. *Environmental Research Letters*, 15, 104093, 1–12.

IPCC (Intergovernmental Panel on Climate Change) (2018) Global warming of 1,5 °C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, 616 pp. Online at: https://www.ipcc.ch/sr15/

Joosten, J. H. J. (1995) Time to regenerate: long-term perspectives of raised bog regeneration with special emphasis on palaeoecological studies. In: Wheeler, B.D., Shaw, S.C., Foit, W.J., Robertson, R.A. (eds.), Restoration of temperate wetlands. Wiley, Chichester, 379–404.

Joosten, H. (1998) Peat as a renewable resource: the road to paludiculture. In: Malterer, T., Johnson, K., Stewart, J. (eds.), Peatland restoration & reclamation. Techniques and regulatory considerations, Jyskä, 56–63.

Joosten, H. (2015) Peatlands, climate change mitigation and biodiversity conservation. An issue brief on the importance of peatlands for carbon and biodiversity conservation and the role of drained peatlands as greenhouse gas emission hotspots. Nordic Council of Minister, 15 pp.

Joosten, H. (2016) Peatlands across the globe. In: Bonn, A., Allott, T., Evans, M., Joosten, H., Stoneman, R. (eds.), Peatland restoration and ecosystem services. Science, policy, and practice. Cambridge University Press, Cambridge, 19–43.

Joosten, H., Tanneberger, F., Moen, A. (eds.) (2017) Mires and peatlands of Europe. Status, distribution and conservation. Schweizerbart Science Publishers, Stuttgart, 780 pp.

Kates, R.W., Clark, W.C., Corell, R., Hall, J.M., Jaeger, C.C., Lowe, I., McCarthy, J.J., Schellnhuber, H.J., Bolin, B., Dickson, N.M., Faucheux, S., Gallopin, G.C., Grübler, A., Huntley, B., Jäger, J., Jodha, N.S., Kasperson, R.E., Mabogunje, A., Matson, P., Mooney, H., Moore, B., O'Riordan, T., Svedlin, U. (2001) Sustainability science. *Science*, 292, 641–642.

Kersten, U., Lindner, H., Melzer, R., Rehberg, U., Staak, R. & Werner, W. (1999) Ergebnisse des Projektes „Regeneration und alternative Nutzung von Niedermoorflächen im Landkreis Ostvorpommern". Stiftung Odermündung, Regionalverband für dauerhafte Entwicklung e.V., Anklam, 57 pp.

Köbbing, J., Thevs, N., Zerbe, S. (2013) The utilisation of reed (*Phragmites australis*): a review. *Mires and Peat*, 13 (01), 1–14.

Krimly, T., Angenendt, E., Bahrs, E., Dabbert, S. (2016) Global warming potential and abatement costs of different peatland management options: A case study for the Pre-alpine Hill and Moorland in Germany. *Agricultural Systems*, 145, 1–12.

Krus, M., Theuerkorn, W., Großkinsky, T., Georgiev, G. (2013) Neuer tragfähiger und dämmender Baustoff aus Rohrkolben. *greenbuilding*, 07-08/2013, 44–47.

Leifeld, J., Menichetti, L. (2018) The underappreciated potential of peatlands in global climate change mitigation strategies. *Nature communications*, 9 (1071), 1–7.

Leifeld, J., Wüst-Galley, C., Page, S. (2019) Intact and managed peatland soils as a source and sink of GHGs from 1850 to 2100. *Nature Climate Change*, 9 (12), 945–947.

Liu, J., Kopold, P., van Aken, P.A., Maier, J., Yu, Y. (2015) Energy storage materials from nature through nanotechnology: a sustainable route from reed plants to a silicon anode for lithium-ion batteries. Angewandte Chemie International Edition, 54, 9632–9636.

Ludwig, G. (2019) Opportunities and challenges of Sphagnum farming & harvesting. Master thesis, JAMK University of Applied Sciences, Jyväskylä, Finland, 33 pp.

Luthardt, V., Wichmann, S. (2016) Ecosystem services of peatlands. In: Wichtmann, W., Schröder, C., Joosten, H. (eds.), Paludiculture - productive use of wet peatlands. Climate protection - biodiversity - regional economic benefits. Schweizerbart Science Publishers, Stuttgart, 13–20.

McKeon-Bennett, M.M., Hodkinson, T.R. (2021) Sphagnum moss as a novel growth medium in sustainable indoor agriculture systems. *Current Opinion in Environmental Science & Health*, 22, 100269, 1–7.

Money, R.P. (1994) Restoration of lowland raised bogs damaged by peat extraction - with particular emphasis on Sphagnum regeneration. PhD thesis, University of Sheffield, UK, 221 pp.

Mulholland, B., Abdel-Aziz, I., Lindsay, R., McNamara, N., Keith, A., Page, S., Clough, J., Freeman, B., Evans, C. (2020) An assessment of the potential for paludiculture in England and Wales. Report to Defra for ProjectSP1218, 98 pp.

Müller, D., Munroe, D.K. (2014) Current and future challenges in land-use science. *Journal of Land Use Science*, 9, 133–142.

Muster, C., Gaudig, G., Krebs, M., Joosten, H. (2015) Sphagnum farming: the promised land for peat bog species? *Biodiversity and Conservation*, 24, 1989–2009.

Muster, C., Krebs, M., Joosten, H. (2020) Seven years of spider community succession in a Sphagnum farm. *The Journal of Arachnology*, 48, 119–131.

Orozco, R., Mosquera-Losada, M.R., Rodriguez, J., Adamseged, M.E., Grundmann, P. (2021) Supportive business environments to develop grass bioeconomy in Europe. *Sustainability*, 13, 12629.

Rawlins, A., Morris, J. (2010) Social and economic aspects of peatland management in Northern Europe, with particular reference to the English case. *Geoderma*, 154, 242–251.

Reinikainen, O., Korpi, J., Tahvonen, R., Näkkilä, J., Silvan, N., Silvan, K. (2012) Harvesting of *Sphagnum* biomass and its use as a growing medium constituent. Proceedings of the 14th International Peat Congress, Stockholm, Sweden, Extended Abstract No. 137, 1–6.

Rodewald-Rudescu, L. (1974) Das Schilfrohr. Die Binnengewässer, 27. Schweizerbart, Stuttgart, 302 pp.

Röder, N., Henseler, M., Liebersbach, H., Kreins, P., Osterburg, B. (2015) Evaluation of land use based greenhouse gas abatement measures in Germany. *Ecological Economics*, 117, 193–202.

Schaller, L. (2014) Landwirtschaftliche Nutzung von Moorflächen in Deutschland - Sozioökonomische Aspekte einer klimaschonenden Bewirtschaftung. PhD thesis, Technical University of Munich, Germany, 296 pp.

Schaller, L., Targetti, S., Villanueva, A.J., Zasada, I., Kantelhardt, J., Arriaza, M., Bal, T., Fedrigotti, V.B., Giray, F.H., Häfner, K., Majewski, E., Malak-Rawlikowska, A., Nikolov, D., Paoli, J.-C., Piorr, A., Rodríguez-Entrena, M., Ungaro, F., Verburg, P.H., van Zanten, B., Viaggi, D. (2018) Agricultural landscapes, ecosystem services and regional competitiveness—Assessing drivers and mechanisms in nine European case study areas. *Land Use Policy*, 76, 735–745.

Schätzl, R., Wild, U., Hoffmann, H. (2006) Gewässerschutz und Landnutzung durch Rohrkolben-bestände. *Wasserwirtschaft*, 11, 24–27.

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*, 16 (13), 1–18.

Swinton, S.M., Lupi, F., Robertson, G.P., Hamilton, S.K. (2007) Ecosystem services and agriculture: Cultivating agricultural ecosystems for diverse benefits. *Ecological Economics*, 64, 245–252.

Tan, Z.D., Lupascu, M., Wijedasa, L.S. (2021) Paludiculture as a sustainable land use alternative for tropical peatlands: A review. *The science of the total environment*, 753, 142111.

Tanneberger, F., Tegetmeyer, C., Dylawerski, M., Flade, M., Joosten, H. (2009) Commercially cut reed as a new and sustainable habitat for the globally threatened Aquatic Warbler. *Biodiversity and Conservation*, 18, 1475–1489.

Tanneberger, F., Tegetmeyer, C., Busse, S., Barthelmes, A. and 55 others (2017a) The peatland map of Europe. *Mires and Peat*, 19 (22), 1–17.

Tanneberger, F., Joosten, H., Moen, A., Whinam, J. (2017b) Mire and peatland conservation in Europe. In: Joosten, H., Tanneberger, F., Moen, A. (eds.), Mires and peatlands of Europe. Status, distribution and conservation. Schweizerbart Science Publishers, Stuttgart, 173–196.

Tanneberger, F., Abel, S., Couwenberg, J., Dahms, T., Gaudig, G., Günther, A., Kreyling, J., Peters, J., Pongratz, J., Joosten, H. (2021) Towards net zero CO_2 in 2050: An emission reduction pathway for organic soils in Germany. *Mires and Peat*, 27 (05), 1–17.

Tata, H.L., Susmianto, A. (2016) Prospek paludikultur ekosistem gambut Indonesia (The prospects for paludiculture in Indonesia's peatland ecosystems). Forda Press, Bogor, 71 pp.

Thesiger, W. (2007) The Marsh Arabs. Penguin Group (first published by Longmanns, Green 1964, by Penguin Books 1967, published with a new introduction in Penguin Classics 2007), 233 pp.

Uda, S.K., Hein, L., Adventa, A. (2020) Towards better use of Indonesian peatlands with paludiculture and low-drainage food crops. *Wetlands Ecology and Management*, 28, 509–526.

UN (United Nations) (2015) Paris Agreement. 25 pp. Online at: https://unfccc.int/sites/default/files/english_paris_agreement.pdf

Urák, I., Hartel, T., Gallé, R., Balog, A. (2017) Worldwide peatland degradations and the related carbon dioxide emissions: the importance of policy regulations. *Environmental Science & Policy*, 69, 57–64.

Wiche, O., Heilmeier, H. (2016) Germanium (Ge) and rare earth element (REE) accumulation in selected energy crops cultivated on two different soils. *Minerals Engineering*, 92, 208–215.

Wichmann, S. (2016) Economic aspects of paludiculture on the farm level. In: Wichtmann, W., Schröder, C., Joosten, H. (eds.), Paludiculture – productive use of wet peatlands. Schweizerbart Science Publishers, Stuttgart, 109–116.

Wichmann, S. (2018) Economic incentives for climate smart agriculture on peatlands in the EU. Proceedings of the Greifswald Mire Centre 01/2018 (self-published, ISSN 2627-910X), 38 pp.

Wichtmann, W. (1999) Nutzung von Schilf (*Phragmites australis*) (The utilisation of reed). Archiv für Naturschutz und Landschaftsforschung 38, 217–231.

Wichtmann, W., Joosten, H. (2007) Paludiculture: peat formation and renewable resources from rewetted peatlands. *IMCG Newsletter*, 3/2007, 24–28.

Wichtmann, W., Schröder, C., Joosten, H. (eds.) (2016) Paludiculture - productive use of wet peatlands. Climate protection - biodiversity - regional economic benefits. Schweizerbart Science Publishers, Stuttgart. 272 pp.

Ziegler, R. (2020) Paludiculture as a critical sustainability innovation mission. *Research Policy*, 49, 103979, 1–9.

Ziegler, R., Wichtmann, W., Abel, S., Kemp, R., Simard, M., Joosten, H. (2021) Wet peatland utilisation for climate protection – An international survey of paludiculture innovation. *Cleaner Engineering and Technology*, 5, 100305, 1–13.

Author's contribution to original publications

The present dissertation consists of five papers published in peer-reviewed scientific journals. My contribution to each of these components is as follows:

Paper I **Commercially viability of paludiculture: A comparison of harvesting reeds for biogas production, direct combustion, and thatching.**
Conceptualisation, fieldwork, stochastic simulation as well as writing and revising the paper were carried out completely by myself.

Paper II **Common reed for thatching – A first review of the European market.**
I drafted the semi-structured questionnaire and carried out the analysis of statistical trade data. J. Köbbing and I jointly conducted the survey and literature review, interpreted the results, wrote and revised the manuscript.

Paper III **Common Reed for Thatching in Northern Germany: Estimating the Market Potential of Reed of Regional Origin.**
I had the idea for the survey among German thatchers and supervised the Bachelor thesis of L. Becker together with V. Beckmann, including conceptualisation, methodology, validation, data curation. The original manuscript was based on the thesis of L. Becker and extensively revised and supplemented by me and V. Beckmann.

Paper IV **Establishing *Sphagnum* cultures on bog grassland, cut-over bogs, and floating mats: procedures, costs and area potential in Germany**
I investigated the procedures, collected cost data, calculated the establishment costs and wrote the manuscript. A. Prager and G. Gaudig provided data on *Sphagnum* biomass accumulation and commented on the draft and the revised version of the manuscript.

Paper V **Paludiculture on former bog grassland: Profitability of Sphagnum farming in North West Germany.**
I collected the cost data, designed and conducted economic analysis and wrote the manuscript. M. Krebs and G. Gaudig supervised the set-up and performance of the Sphagnum farming field trial and contributed data on *Sphagnum* biomass accumulation. S. Kumar contributed data on bulk density. All authors revised the manuscript critically before (re)submission.

____

Sabine Wichmann

I confirm the author contribution statements.

Greifswald, ____

(date) Prof. Dr. Dr. h. c. Hans Joosten

Paper I

Wichmann, S. (2017)

Commercial viability of paludiculture:

A comparison of harvesting reeds for biogas production, direct combustion, and thatching.

Ecological Engineering 103: 497–505.

Ecological Engineering 103 (2017) 497–505

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Commercial viability of paludiculture: A comparison of harvesting reeds for biogas production, direct combustion, and thatching

Sabine Wichmann[a,b,*]

[a] DUENE e.V. and Institute of Botany and Landscape Ecology, Ernst Moritz Arndt University, Partner in the Greifswald Mire Centre, Soldmannstraße 15, D-17487 Greifswald, Germany
[b] Institute of Sustainable Development of Landscapes of the Earth (DUENE e.V.), Soldmannstraße 15, 17489 Greifswald, Germany

ARTICLE INFO

Article history:
Received 16 July 2015
Received in revised form 7 February 2016
Accepted 14 March 2016
Available online 30 March 2016

Keywords:
Phragmites australis
Peatland
Wetland management
Tracked machinery
Profitability
Monte Carlo simulation

ABSTRACT

Since disservices and the finite nature of agriculture on drained peatlands are increasingly recognised, land use options for wet or rewetted peatlands (paludiculture) are recommended as sustainable alternatives. Their economic viability at the farm level, however, is largely unknown. This paper addresses managing reed-dominated (*Phragmites australis*) vegetation stands with special-purpose tracked machinery in central Europe. Three options of biomass harvest for energetic and material use were investigated. Contribution margin accounting estimated the income left after subtracting variable costs and fixed machinery costs. Stochastic scenario analysis (Monte Carlo method) revealed a wide range of possible outcomes from ca. € −1000 to € 1500 ha^{-1} yr^{-1}. Harvesting summer reed for biogas production is the least profitable option, winter mowing for direct combustion can be cost-efficient, and reed for thatching is clearly the most profitable. Cumulative probability distributions identified risks of 98%, 18%, and <1% respectively, that revenues for biomass cannot cover harvesting costs. The feasibility and competitiveness of the three harvesting regimes are principally influenced by the availability of mature technology, legal restrictions, the entitlement to agricultural subsidies, a remuneration of external benefits, and the opportunity costs of present farming activities. Therefore, laws and policies determine whether a balanced provision of ecosystem services is hindered or promoted in peatlands used for agriculture.

1. Introduction

Draining peatlands for agriculture has caused the successive degradation of ecosystem functions. The resulting loss of biodiversity, nutrient discharge, greenhouse gas emissions, soil degradation, and subsidence have led to increasing recognition of and value placed on ecosystem services provided by wet peatlands (Maltby, 1986; Joosten and Clarke, 2002; Groot et al., 2006; Turner et al., 2008). Paludiculture, i.e. agriculture on wet or rewetted peatlands (Wichtmann and Joosten, 2007), has the potential to balance provisioning, regulating, and cultural services (Luthardt and Wichmann, 2016); keep organic soils in long-term use (Joosten et al., 2012); and sustainably produce biomass for renewable energy or as a raw material (Wichtmann and Wichmann, 2011). For decades, scientists have suggested to cultivate wetland-adapted crops and refine traditional uses (Morton and Snyder, 1976; Kresovich et al., 1981; Porter et al., 1992; Verhoeven and Setter, 2009; Knox et al., 2015). In recent years, however, major international bodies have recommended paludiculture as a viable option (EU, 2013; FAO: Biancalani and Avagyan, 2014; IPCC, 2014; IUCN: Cris et al., 2014).

Since land users adopt sustainable practices on peatlands only "if they are practical and financially viable" (Rawlins and Morris, 2010), the issue is the extent to which paludiculture – besides providing external benefits – is profitable at the farm level. The database of potential paludicultural plants (Abel et al., 2013) contains 800 species that thrive under wet conditions and indicates appropriate options for using their biomass. In particular, cultivating emergent wetland plants as a bioenergy source and building or insulation material is both feasible and practical (Wichtmann and Schäfer, 2007; Wichtmann and Tanneberger, 2011). An economic harvest of taxa such as reed (*Phragmites australis*), cattail (*Typha* spp.), and sedges (*Carex* spp.) requires efficient machines that are adapted to saturated organic soils by having a low ground pressure. 'Seiga' machines, equipped with balloon tyres, have been used to harvest thatching reed since the 1950s (Björk and Granéli, 1978). Modified snow groomers and newly developed special-purpose tracked machinery are increasingly used for biomass harvest (Wichmann et al., 2016), including the large-scale conservation management of fens (Kotowski et al., 2013).

* Tel.: +49 3834 86 4143; fax: +49 3834 86 4107.
E-mail address: wichmann@uni-greifswald.de

http://dx.doi.org/10.1016/j.ecoleng.2016.03.018
0925-8574/

Research has focused on the influence of biomass harvest on productivity and stand structure (Engloner, 2009), botanical diversity (Kotowski et al., 2013), wildlife (Valkama et al., 2008), nutrients (Vymazal, 2005), and greenhouse gas emissions (Günther et al., 2014), but the economics of wetland management has been largely neglected. To date, no study exists with reliable data on the costs of biomass removal based on large-scale and long-term experience with special-purpose machinery. This article explores the cost-effectiveness of harvesting reeds in central Europe, identifies the variables with the greatest influence on profitability, compares advantages and disadvantages of three harvesting regimes, and discusses aspects that influence their feasibility and competiveness.

2. Materials and methods

2.1. Harvesting regimes

Economic costs and benefits were estimated for the harvest of reed-dominated vegetation stands with tracked vehicles. These machines are suitable for an efficient, large-scale harvest and are equipped with specific devices adapted for the intended use of biomass (Fig. 1). The three options of biomass utilisation considered are applied by pioneering commercial plants (biogas production, combustion) or widely established with an international market (thatching):

(a) Chopped biomass for biogas production ['chaff']

Green biomass is cut in summer with a rotary mower or cutter bar and is then windrowed in one pass. In a second pass, the swath is picked up by a forage wagon or gathered by a chopper and placed into a trailer (Fig. 1a and b). The finely chopped biomass is processed in biogas plants adapted to green grass-like material to generate electricity and heat.

(b) Round bales for direct combustion ['bales']

Biomass is harvested on dry winter days, when its moisture content is sufficiently low to prevent excessive heating and moulding during storage, and to cut and press it into round bales in a single pass (Fig. 1c and d). A separate vehicle equipped with a crane picks up the bales and transports them to the edge of the field. The bales are burnt in combustion plants designed to generate heat (and in the high power range also electricity) from materials such as straw or *Miscanthus*.

(c) Bundles for thatching ['bundles']

Thatching reed is harvested in winter when the leaves have fallen and the moisture content is low. In one pass, the long, straight culms are mown with a cutter bar, brushed for an initial cleaning and bound into bundles with a circumference of approximately 65–70 cm (Fig. 1e and f). Several hundred bundles are bound into one large bale and transported to the edge of the field with a separate vehicle. After the harvest and further drying, bundles are opened, cleaned and bound into tight bundles (55–60 cm circumference) ready for sale and thatching.

2.2. Data collection

In-depth, semi-structured interviews were conducted with reed cutters and landscape managers with extensive (20–30 years) experience in wetland-adapted machinery, site productivity and revenues (Germany: n = 6, Netherlands: n = 2, Poland: n = 1, Austria: n = 1). A standardised questionnaire was sent to all biogas plants in the German federal state of Mecklenburg-Western Pomerania (n = 237, 19% response rate) to investigate the current use of grass-like biomass in NE Germany and the willingness to accept biomass from paludiculture. Labour time and acreage performance (e.g. the time required for mowing, chopping and transporting biomass) were measured during field tests for the 'chaff' and 'bundles' harvesting regimes using GPS tracking (logger Wintec WBT-202) and a stopwatch. Literature was used to verify estimates of biomass productivity, revenues, and harvesting performance.

Table 1
Extended contribution margin (CM) accounting to estimate profitability: revenues have to cover not only variable costs (CM I) but also fixed costs of specialised, single-purpose machinery (CM II).

Revenues from the sale of biomass:
Biomass yield × price
Minus variable costs:
– direct costs (seedlings, fertiliser, pesticides)[a]
– variable machinery costs
– labour costs
= Contribution margin I
Minus attributable fixed costs:
– fixed machinery costs
= Contribution margin II

[a] Not applicable, since harvest of existing vegetation stands is assumed.

2.3. System boundaries

Cost accounting was performed to calculate harvesting costs and to compare the expenses and revenues of each regime. Operating costs included all costs of harvesting, transporting (to the field edge) and processing needed to sell the biomass for energy or material use. Costs of further transport and storage vary widely; in specific cases they can be calculated using data for handling silage, straw, or hay in conventional agriculture.

The calculations included variable machinery costs (e.g. fuel, machine care) and labour costs, which changed with the production volume, and fixed machinery costs (e.g. depreciation, insurance), since they could be assigned directly to the harvesting regimes (Table 1). General and administrative costs, which vary considerably among companies, and site-specific costs or revenues (e.g. land lease, direct payments) were excluded.

2.4. Stochastic simulation

Stochastic scenario analysis was performed using Monte Carlo simulations (Hardaker et al., 2004) to account for uncertainty in and ranges of data. Each input variable of the CM II calculation model was given a range of values and a probability distribution (Tables 3 and 4). Depending on the variable and data quality, the probability distribution was defined as uniform (e.g. purchase costs of machinery) or triangular (e.g. yield) by setting maximum and minimum values (and the mode, for the latter). Simple positive or negative correlation factors were assumed to express interdependence between single variables (Table 2), e.g. higher biomass yield requiring more time to harvest and consequently inducing higher harvesting costs per hectare. In calculating the fixed machinery costs, expensive machinery was assumed to have more operating hours per year and a higher residual value.

Computer-based Monte-Carlo simulations were performed with @RISK 6 software (Palisade Corporation, Ithaca, New York, USA) used as an add-in for spreadsheet software (Microsoft® Office Excel 2013). A large number of iterations (10,000) were generated for each harvesting regime. Input values were randomly selected according to the conditions defined for each parameter. Use of the Latin hypercube method ensured stratified random sampling

Fig. 1. Tracked machinery with low ground pressure and equipped with special devices to harvest (a and b) finely chopped biomass for biogas production, (c and d) round bales for direct combustion, and (e and f) bundles for thatching (author's photos, except (c) J. Krail, (d) I. Mirowski, and (e) Bahnsen-Clausen GbR).

Table 2
Factors assumed for the correlation between single input variables (A, B) to facilitate scenarios based on reasonable value combinations.

Input variable (A)	Input variable (B)	'chaff'	'bales'	'bundles'
Yield	mowing performance	0.5	0.7	0.7
Yield	chopping performance	0.7	n/a	n/a
Yield	removing biomass	n/a	0.7	n/a
Purchase costs of				
- mowing machine	residual value	0.7	n/a	n/a
	operating time	0.7	n/a	n/a
- tractor (towing vehicle)	residual value	0.7	n/a	n/a
	operating time	0.7	n/a	n/a
- forage wagon	operating time	0.7	n/a	n/a
- harvester	residual value	n/a	0.7	0.7
	operating time	n/a	0.7	0.7

Table 3
Variables that determine revenue, with their ranges and, for triangular probability distributions, modes (in brackets). The conservative estimates are based on (a) survey, (b) field, and (c) literature data.

Variable	Unit	'chaff'	'bales'	'bundles'	Source
Yield (gross)	t DW ha^{-1}	3–8 (5)	5–15 (8)	n/a	a, c
Yield (net)	bundles ha^{-1}	n/a	n/a	300–1000 (500)	a
Factor of loss	%	15–25 (20)	15–25 (20)	n/a	c
Water content	%	30–50[a]	15–25 (20)	n/a	b, c
Price (chaff)	€ (t FW)	0–35 (10)	n/a	n/a	a
Price (bales)	€ (t DW)	n/a	45–110 (65)	n/a	c
Price (bundles)	€ (bundle)	n/a	n/a	1.90–2.50 (2.00)	a

DW = dry weight, FW = fresh weight.
[a] No mode given due to high data variability.

Table 4
Variables that determine cost, with their ranges and, for triangular probability distributions, modes (in brackets). Estimates are based on (a) survey, (b) field, and (c) literature data.

Variable	Unit	'chaff'	'bales'	'bundles'	Source
Purchase costs					
- mowing machine	€	57,000–148,000	n/a	n/a	a
- tractor (towing vehicle)	€	57,000–230,000	n/a	n/a	a
- forage wagon	€	50,000–135,000	n/a	n/a	a
- tracks	€	15,000–25,000 (20,000)	15,000–25,000 (20,000)	15,000–25,000 (20,000)	a
- mowing device	€	10,000–20,000	10,000–20,000	n/a	a
- harvester	€	n/a	55,000–370,000	65,000–350,000[a]	a
- transporting machine/loading crane	€	n/a	30,000–50,000	20,000	a
Machine lifespan					
- mowing machine/tractor	yr	10–25 (15)	n/a	n/a	a
- forage wagon	yr	5–10	n/a	n/a	a
- tracks	yr	4–6	4–6	4–6	a
- mowing device	yr	5–10	5–10	10–20 (15)	a
- harvester	yr	n/a	8–15 (12)	10–20 (15)	a
- transporting machine	yr	n/a	8–15 (12)	10	a
Residual value					
- mowing machine/tractor	€	20,000–80,000 (30,000)	n/a	n/a	a
- forage wagon	€	2000	n/a	n/a	a
- tracks	€	2000	2000	2000	a
- harvester	€	n/a	5000–10,000	20,000–80,000 (30,000)	a
- transporting machine	€	n/a	2000	2000	a
Operating time					
- mowing machine	$h\,yr^{-1}$	300–1200	n/a	n/a	a
- tractor + forage wagon	$h\,yr^{-1}$	300–1200	n/a	n/a	a
- harvester	$h\,yr^{-1}$	n/a	350–600 (450)	150–400 (250)	a
- transporting machine	$h\,yr^{-1}$	n/a	350–600 (450)	150–400 (250)	a
Interest rate	%	3–5	3–5	3–5	c
Insurance per machine or wagon	$€\,yr^{-1}$	800–5000 (2000)	800–5000 (2000)	800–5000 (2000)	a
Insurance per transporting machine	$€\,yr^{-1}$	n/a	500–1000	500–1000	a
Machine care					a
- mowing	$€\,yr^{-1}$	6000–12,000 (10,000)	n/a	n/a	a
- chopping	$€\,yr^{-1}$	10,000–35,000 (20,000)	n/a	n/a	a
- mowing + baling or bundling	$€\,yr^{-1}$	n/a	10,000–35,000 (20,000)	5000–8000 (7000)	a
- transporting	$€\,yr^{-1}$	n/a	5000–7000	3000–5000	a
Fuel					
- mowing	$l\,h^{-1}$	8–16 (14)	n/a	n/a	a
- chopping/loading	$l\,h^{-1}$	12–25 (18)	n/a	n/a	a
- harvesting	$l\,h^{-1}$	n/a	15–25 (20)	10–18 (12)	a
- transporting	$l\,h^{-1}$	n/a	10–15 (12)	8–15 (12)	a
- price of diesel (net)[b]	$€\,l^{-1}$	1.00–1.30	1.00–1.30	1.00–1.30	a, c
- lubricants + baling twine	$€\,h^{-1}$	0.30–1.00	0.30–1.00	0.30–1.00	a
Performance					
- mowing	$h\,ha^{-1}$	0.4–2.2	n/a	n/a	a, b, c
- chopping	$h\,ha^{-1}$	0.9–5.2	n/a	n/a	a, b, c
- harvesting	$h\,ha^{-1}$	n/a	1–4 (2)	n/a	a, c
- transporting	$h\,ha^{-1}$	n/a	1–4 (2)	n/a	a, c
- harvesting	bundles h^{-1}	n/a	n/a	150–500 (325)	a, b
- transporting	bundles h^{-1}	n/a	n/a	150–500 (325)	a, b
- processing	bundles h^{-1}	n/a	n/a	30–50 (40)	a, b
Labour costs (direct + indirect)	$€\,h^{-1}$	10–25	10–25	10–25	a

[a] Including mowing device and tracks.
[b] No tax reduction for agricultural use.

from the entire range of distribution (Palisade, 2013). Predictions were presented graphically (e.g. relative frequency, cumulative distribution function) and with statistical indices. Spearman's rank correlation was used for stochastic sensitivity analysis to identify the input variables with the highest influence on the output values 'harvesting costs' and 'contribution margin II'.

3. Results

3.1. Values of input variables for revenues and costs

Revenues are determined by biomass yield and price (Table 3). Yields tend to be lower on summer-mown sites ('chaff') than on winter-mown sites ('bales', 'bundles'), since reed is weakened when cut during the growing season (Asaeda et al., 2006). The yield of thatching reed is given in bundles, each of which has a weight of 4–5 kg, and represents only part of the overall stand productivity since cleaning the bundles during and after harvest reduces the reed mass by up to 50%.

The survey of biogas plants revealed little acceptance of wetland biomass for anaerobic digestion, which results in a low price for green chaff. While 23% already use and 47% are interested in using a grass-like co-substrate to produce biogas, there was little interest in biomass from paludiculture (29%). Most of the existing plants (53%) were not adapted to process grass-like biomass. The medium price level for reed bales mirrors the German market for straw bales (BauernZeitung, 2010–2014), since straw can be burned in the place of reed. Thatching bundles have the highest prices, even though the prices given reflect producer prices; end-consumer prices of thatching reed traders may be higher.

Harvesting costs, especially fixed machinery costs, are influenced by many variables (Table 4). The performance (i.e. the time needed for harvest) determines the overall costs per unit. The results represent the different working conditions of the interviewees. The wide range of values for certain variables (e.g. harvester purchase cost, operating time per year, acreage performance) reflects the wide variety of machines, capacity utilisation rates, and site conditions.

3.2. Chaff for biogas

For chaff for biogas production, CM II ranged from € −1036 to € 179 ha^{-1} yr^{-1} (Fig. 2a), with a mode of € −195 (Table 5). Excluding the upper and lower 5% of the right-skewed frequency distribution resulted in a range of € −599 to −37 ha^{-1} (all negative values) (Fig. 2a). The factors with the most influence on CM II were acreage performance of chopping/transporting (r_s = -0.75), biomass yield (r_s = −0.52) and revenue per tonne (r_s = 0.44). There was a 98% risk that revenue would not cover harvesting costs (Fig. 2a). Setting the price at the maximum value of € 35 t^{-1} fresh weight (Table 3) or assuming a net support of € 200 ha^{-1} (subsidies minus rent), the probability of loss remained high: 67% and 68%, respectively (calculations not shown). Harvesting costs were mainly influenced by the acreage performances of chopping/transporting (r_s = 0.90) and mowing (r_s = 0.21), as well as the yearly operating hours of tractors and forage wagons (r_s = −0.25) due to their influence on fixed machinery costs.

3.3. Round bales for combustion

For bales for combustion, CM II ranged from € −287 to € 677 ha^{-1} yr^{-1}, with an 18% risk that revenue would not cover harvesting costs (Fig. 2b). Due to the left-skewed distribution, the mode of € 53 ha^{-1} was lower than the median and mean (€ 100 and € 115 ha^{-1}, respectively). The harvesting regimes for chaff and bales had similar costs per hectare (mode: € 397 and € 419, respectively, with a greater range for chaff, Table 5). The higher revenue from bales resulted in higher CM II. The high influence of the revenue level on income was reflected by r_s = 0.80 between biomass price per tonne and CM II. Raising the minimum biomass price (Table 3) from € 45 to € 60 t^{-1} DW, while leaving the mode (€ 65), maximum (110 €) and all other variables unchanged, reduced the risk of loss from 18% to 6% (calculations not shown). Other variables had less influence than biomass price, such as purchase cost of the harvester (r_s = −0.33), time needed to transport biomass (r_s = 0.33), and yield per hectare (r_s = 0.30). Harvesting costs were determined mainly by the acreage performances of mowing and baling (r_s = 0.76) and transporting bales to the edge of the field (r_s = 0.40), followed by purchase costs (r_s = 0.39) and residual value of the harvester (r_s = 0.33).

3.4. Bundles for thatching

For bundles for thatching, the probability of a loss was near 0% (Fig. 2c). CM II ranged from € −162 to € 1542 ha^{-1} (mode: € 572 ha^{-1}) and from € 174 to € 1006 ha^{-1} when the upper and lower 5% were excluded (Table 5). The factors with the most influence on CM II were the number of bundles per hectare (r_s = 0.79) and harvesting performance (r_s = 0.76), followed by labour costs (r_s = −0.35) and the price per bundle (r_s = 0.27). Harvesting and processing costs per hectare were influenced mainly by the amount of biomass (r_s = 0.61), labour cost (r_s = 0.58), and residual value (r_s = 0.19) and purchase cost (r_s = 0.16) of the harvester. Bundle production had the highest variability in CM II, illustrated by the lower ascend of the cumulative probability distribution (Fig. 2) and a standard deviation of € 254 ha^{-1} yr^{-1} compared to € 173 ha^{-1} yr^{-1} for chaff and € 127 ha^{-1} yr^{-1} for bales (Table 5).

4. Discussion

4.1. Assessing profitability

Cost accounting clearly showed that there is not only one valid answer whether paludiculture is profitable. Decision makers (e.g. farmers, site managers, politicians) require precise figures, but with current knowledge, point estimates of profitability are easily miscalculated, and deterministic accounting using fixed values is restricted to specific cases. Monte Carlo simulations show the possible range of loss or profit, as well as the mode, and thus provide a more accurate picture of reality.

When harvesting reeds with tracked machinery, CM II ranges from ca. € −1000 to € 1500 ha^{-1} yr^{-1}. The distinction of the three production regimes is evident in Fig. 2, and by comparing modes (€ ha^{-1}) and risks of loss (%) (Table 5):

- Harvesting chaff for biogas production is not profitable (€ −195 ha^{-1}; 98%) and remains the least profitable option when maximum biomass prices or subsidies are assumed.
- Harvesting bales for combustion is more profitable (€ 53 ha^{-1}; 18%). This option appears to cover costs, except when several influential input variables have pessimistic values, especially biomass price.
- Harvesting bundles for thatching is the most profitable option (€ 572 ha^{-1}, <1%). Despite having the highest harvesting costs (Table 5), the high revenue for quality reed clearly favours harvesting for thatching rather than for combustion or biogas production (Fig. 2).

Biomass yield and price per tonne or bundle were identified as input parameters that strongly influence profitability of all three harvesting regimes. These site- and market-specific values can be easily adapted to specific situations to reduce the range of predictions and allow decision makers to perform a more precise economic assessment. Labour cost was more influential for bundle profitability than for the other two regimes due to the higher demand for labour. In addition to the operators of the harvesting and transporting machines, two more people are usually needed on the harvester to gather the bundles and stow them on the platform (Fig. 1e). An additional processing step is required after the harvest for cleaning (combing) and dressing the reed bundles. The acreage performance of harvesting and transporting machinery plays a decisive role in all production regimes. This crucial variable illustrates the limitations of this study, which is based on the experiences of a few practitioners, and the validity of data on costs, in general. The wetland-adapted machines currently used are usually immature prototypes or modified second-hand snow groomers. It is assumed that improved technology and logistics, increased capacity utilisation of machinery, and economy-of-scale effects would reduce costs. Acreage performance depends greatly on site conditions (e.g. soil trafficability, field size, access points) and the amount of biomass produced. This study is valuable in its use of data of special-purpose harvesting machinery that depicts real life instead of a desk study based on assumptions or on standard data from conventional farm machinery. Large-scale, long-term experiences of practitioners allowed including data, which cannot be captured by pilot trials such as machine lifespan and maintenance. Detailing all input variables and assumptions allows further application, revision and comparison of the results.

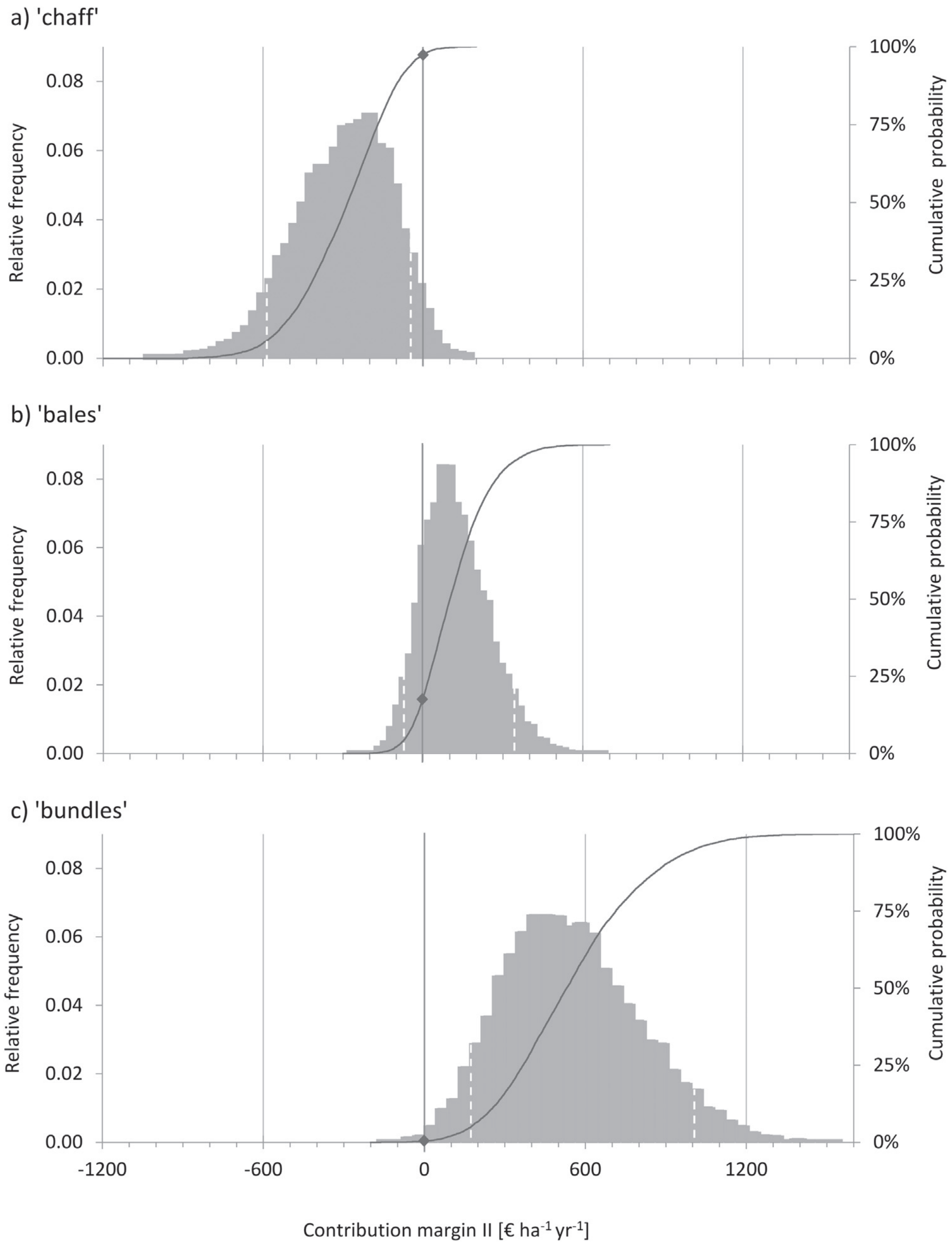

Fig. 2. Relative frequencies (histograms) and cumulative probabilities (solid lines) of profitability (contribution margin II) of harvesting reed (a) chaff for biogas production, (b) bales for direct combustion, and (c) bundles for thatching, based on Monte Carlo simulations with 10,000 iterations for each regime. Vertical dashed lines delineate 90% of the predictions. Diamonds (♦) on cumulative distributions at x = 0 indicate a risk of (a) 98%, (b) 18%, and (c) <1% that revenues cannot cover harvesting costs.

Table 5
Results of Monte Carlo simulation on extended contribution margin (CM II) accounting for three reed harvesting regimes.

Result	Unit	'chaff'	'bales'	'bundles'
Range of revenue (mode)	€ ha^{-1} yr^{-1}	2–608 (106)	208–1215 (465)	607–2380 (1076)
Range of costs (mode)	€ ha^{-1} yr^{-1}	112–1138 (397)	195–805 (419)	324–1463 (640)
CM II				
– Range (100%)	€ ha^{-1} yr^{-1}	−1036–179	−287–677	−162–1542
– Range (90%)[a]	€ ha^{-1} yr^{-1}	−599–−37	−72–343	174–1006
– Mode	€ ha^{-1} yr^{-1}	−195	53	572
– Median	€ ha^{-1} yr^{-1}	−283	100	530
– Mean	€ ha^{-1} yr^{-1}	−297	115	551
– Standard deviation	€ ha^{-1} yr^{-1}	173	127	254
Risk of loss	*%*	*97.5*	*17.8*	*0.4*

[a] Excluding upper and lower 5% of frequency distribution.

Table 6
Advantages and disadvantages that influence the commercial viability of reed harvesting regimes.

	'chaff'	'bales'	'bundles'
Implementation			
Profitability (without subsidies)	– –	+/–	++
Mature harvesting machinery	+	–	++
Mature utilisation technology	+	++	++
Market demand and acceptance	–	+	++
Regulations			
Legal (restricting harvest)	+/–	–	–
Policy (agricultural subsidies)	+	– –	– –
External benefits, potentially remunerated			
Conservation (e.g. habitats of target species)	++	+/–	+/–
Nutrient removal	++	+/–	+/–
Peat preservation	++	++	++

Reed is the most widespread wetland plant in Europe, and its long tradition of multiple uses (Rodewald-Rudescu, 1974; Haslam, 2010) has been revitalised by recent research in several European countries (e.g. Ikonen and Hagelberg, 2007; Kitzler et al., 2012; Kask, 2013). Nevertheless, literature on harvesting costs of reeds or wetland biomass in general is rare. The reliability of the data that do exist is limited due to insufficient information about the assumptions behind calculations (e.g. machinery, site conditions, included vs. excluded costs). Figures from the literature (often grey) are cited and processed, but usually no new data are collected. This is illustrated by a study on cultivating reed for bioenergy in the Netherlands (Kuhlman et al., 2013). Its cost estimates were based on a report (Daatselaar et al., 2009) which derived the costs of harvesting chopped material (Hansson and Fredriksson, 2004) from a Swedish thesis studying summer reed harvest in a lake with a mowing boat and chopping at the landing site (Fredriksson, 2002). Data from large-scale harvesting of reed for paper and energy in China (Brix et al., 2014; Köbbing et al., 2014) or cattails for energy and phosphorus removal in Canada (Grosshans et al., 2015; Grosshans and Grieger, 2015) cannot be used in the current context because frost, dry periods or drainage for harvest allowed for using conventional farm machinery.

Two methods of data collection improve the knowledge about harvesting costs and the ability to estimate profitability:

(a) Extended surveys among practitioners to reveal long-term experience with specialised machinery (e.g. investment, maintenance, fuel consumption, down-times due to machine failures, lifespan, residual value)
(b) Collecting field data to assess and model acreage performance (e.g. driving speed, turning manoeuvres, loading, unloading) in dependence of harvesting machinery, processing methods, site conditions, and the amount of biomass produced (see de Jong et al., 2003). Large-scale field tests that vary only one factor at a time should be conducted to obtain comparable and reliable data.

4.2. *Beyond profitability*

In addition to revenue from biomass sale and harvesting costs, each harvesting regime has specific advantages and disadvantages that influence its commercial viability within the current general framework (Table 6). The state of implementation, legal or policy regulations, and the potential remuneration of external benefits have a decisive influence on profitability and feasibility.

The summer harvest for *biogas generation* requires financial support to cover harvesting costs. Agricultural subsidies (paid if wet meadows are classified as grassland) and incentives via agri-environmental schemes or conservation management contracts (remunerating external benefits such as habitat protection or nutrient removal) can compensate low profitability. Similar results are anticipated for reeds dominated by reed canary grass (*Phalaris arundinacea*) or sedges (*Carex* spp.), if site conditions require a harvest by tracked vehicles. Limited funds for conservation management have forced the machines to become more efficient (Fig. 1a, b). However, practices are usually limited to mowing. The biomass produced is still largely seen as waste, and options for using it are rarely developed. Biomass processing is restricted to local markets due to the high costs of transporting fresh biomass with a high water content. Further incentives are needed for the processing stage to overcome the low acceptance of practitioners and help widely established wet fermentation biogas plants adapt to use biomass of low digestibility (see Section 3.1). The energy yield from grass silage is generally lower than its biomass yield because some of the energy remains in unconverted fermentation residues or becomes waste heat when electricity is generated (Rösch et al., 2009). Energy conversion rates are much higher for combustion of hay (Rösch et al., 2009), but drying fresh summer mown biomass in the field is restricted by water tables near or above soil surface.

The use of winter-mown reed for *direct combustion* is a promising option for wider application. It enables harvesting sites that would not meet the quality demand of thatching reed, including heterogeneous or old vegetation stands, and profitability can be achieved. Winter harvested reed biomass is well suited for combustion in state-of the-art furnaces designed for materials such as straw or *Miscanthus*; this promotes decentralised production of renewable energy (Barz et al., 2007; Kitzler et al., 2012). However, a major obstacle is that specialised harvesting machinery and logistics are still considered immature (Komulainen et al., 2008). Currently, machines for harvesting bales in one pass have been tested only in pilot trials (Fig. 1c). Supporting research and development of harvesting technology can promote the use of reed for combustion.

Harvesting *thatching reed* appears to be not only the most profitable (Fig. 2) but also the most established option. Apart from the predominant use as traditional roofing material, long reed culms harvested as bundles are processed to mats (screens, plaster base), insulation panels and partition walls for construction (e.g. Köbbing et al., 2013). The current international market for thatching reed has stimulated development of highly efficient machinery in Western Europe (Fig. 1e and f) to compete with low labour costs in reed-exporting countries such as Hungary, Romania, Turkey, and China. However, 70–85% of reed bundles are imported in traditional thatching countries such as Germany, the Netherlands, the UK and Denmark (Wichmann and Köbbing, 2015). Nowadays, only some of their domestic reed beds can provide high-quality reed and the harvest is spatially and temporally restricted by nature conservation. Thatching reed is not considered as an agricultural product and thus its harvest is not eligible to receive agricultural subsidies from the European Union. Domestic production could be increased by increasing the area of reed beds to reduce competition with conservation measures, adapting laws and policies, and promoting investment in efficient machinery to ensure competiveness on the international market.

Since the analysis is based on the current context of large-scale harvesting of semi-terrestrial reed stands with tracked machinery in central European countries, transferring its results to other sites (e.g. lakes, coasts), plant communities (e.g. cattails), harvesting technologies (e.g. Seigas with balloon tyres), countries (e.g. legal and policy conditions), or uses for biomass (e.g. pulp and paper) requires further investigation.

Efficient harvesting techniques and viable options for using wetland biomass are also interesting when management focuses on biodiversity and regulating services. Semi-natural wetlands are mown to maintain and improve habitat conditions for rare species

(Hawke and José, 1996; Benstead et al., 1999; Middleton et al., 2006; Tanneberger et al., 2009). Wetlands dominated by invasive species are managed to foster native vegetation (Jakubowski et al., 2010; Escutia-Lara et al., 2012; Lishawa et al., 2015). Marshes and constructed wetlands are harvested for nutrient removal or to preserve and enhance the system's ability to take up nutrients (Toet et al., 2005; Cicek et al., 2006; Meerburg et al., 2010). The use of harvested biomass is expected to improve the cost-benefit ratio of these measures (Jakubowski et al., 2010; Lachmann et al., 2010; Liu et al., 2012).

Remunerating external benefits of multi-functional peatlands can improve the low profitability of paludiculture at the farm level and stimulate large-scale implementation. For example, introducing Polish agri-environmental payments for late summer mowing of fen peatland sites, either occupied by Aquatic Warblers (ca. € 334 ha^{-1} yr^{-1}) or with a typical vegetation indicating potential habitat, resulted in over 10,000 ha of public land managed by local farmers (Lachmann et al., 2010). Ecosystem services such as fostering biodiversity, removing nutrients, reducing GHG emissions, decreasing soil degradation and subsidence, buffering water, and increasing recreation value have been assessed and partly monetized (e.g. Schäfer, 2004; Grandiek et al., 2007; Blaeij and de Reinhard, 2008; Polman et al., 2014; Joosten et al., 2015).

Appropriate measures and the amount of support necessary to convince practitioners to switch to paludiculture depend on the baseline and should be decided after analysing the specific situation (Schaller et al., 2011; Table 6). This paper shows for reeds that dependence on financial incentives differs between and within harvesting regimes (Fig. 2). Additionally, the opportunity cost (i.e. profit of an alternative production method forgone) to overcome impact commercial viability of paludiculture; it increases with the intensity of current land use and varies greatly among countries and regions. Changing conditions, such as higher production costs in peatlands due to rising water tables, increasing energy prices, and technical progress in processing biomass, will favour reed cultivation in the future in contexts in which it currently cannot compete with conventional agriculture (Kuhlman et al., 2013).

However, most contexts currently support the continuation of conventional agriculture, despite of increased awareness of drained peatland disservices. Regina et al. (2015) criticise the lack of policy coherence, e.g. ignoring climate policies when planning land-use or agricultural policies. They suggest a Common Agricultural Policy that does not increase artificially the profitability of agriculture on drained peatlands, but enables managing organic soils sustainably to minimise loss of the peat layer.

4.3. Conclusion

Since paludiculture is recommended as sustainable land use option for peatlands, its viability at the farm level was evaluated for three established reed harvesting regimes. The ability of revenue from selling reed biomass to cover its harvesting costs is an important piece of the puzzle. However, laws and policies ultimately determine whether a balanced provision of ecosystem services is hindered or encouraged in peatlands used for agriculture.

Acknowledgements

Many thanks go to all the practitioners, who allowed the collection of field data, shared their long-term experiences, and discussed estimates. Hans Joosten, Franziska Tanneberger, Tobias Dahms, Volker Beckmann, and Wendelin Wichtmann provided valuable comments on an earlier version of the manuscript. This study began as part of the project "Vorpommern Initiative Paludiculture" (2010–2013) within the Framework Program "Research for Sustainable Development" funded by the German Federal Ministry of Education and Research and was completed within the "Paludi-Pellets-Project" (2013–2015) funded by the European Union through the European Social Fund.

References

Abel, S., Couwenberg, J., Dahms, T., Joosten, H., 2013. The database of potential paludiculture plants (DPPP) and results for western pomerania. Plant Divers. Evol. 130 (3), 219–228.

Asaeda, T., Rajapakse, L., Manatunge, J., Sahara, N., 2006. The effect of summer harvesting of *Phragmites australis* on growth characteristics and rhizome resource storage. Hydrobiologia 553 (1), 327–335, http://dx.doi.org/10.1007/s10750-005-1157-6.

Barz, M., Wichtmann, W., Ahlhaus, M., Timmermann, T., 2007. Utilisation of common reed as an energy source. Proceedings of the 15th European Biomass Conference and Exibition 2007, Berlin, Germany, 527–531.

BauernZeitung, 2010–2014. several issues, Deutscher Bauernverlag GmbH, Berlin.

Benstead, P.J., José, P.V., Joyce, C.B., Wade, P.M., 1999. European Wet Grassland. Guidelines for Management and Restoration. The Royal Society for the Protection of Birds, Sandy, 169 pp.

Biancalani, R., Avagyan, A., 2014. Towards climate-responsible peatlands management. Mitigation of Climate Change in Agriculture Series 9. FAO, Rome, 100 pp http://www.fao.org/3/a-i4029e.pdf.

Björk, S., Granéli, W., 1978. Energy reeds and the environment. Ambio 7, 150–156.

Blaeij, A., de Reinhard, S., 2008. Een waterpark als alternatief. MKBA aanleg multifunctioneel helofytenfilter op Waterpark Het Lankheet. Rapport 2008–061. LEI Wageningen UR, Den Haag, 75 pp http://library.wur.nl/WebQuery/edepot/121058.

Brix, H., Ye, S., Laws, E.A., Sun, D., Li, G., Ding, X., Yuan, H., Zhao, G., Wang, J., Pei, S., 2014. Large-scale management of common reed, *Phragmites australis*, for paper production: a case study from the Liaohe Delta, China. Ecol. Eng. 73, 760–769.

Cicek, N., Lambert, S., Venema, H.D., Snelgrove, K.R., Bibeau, E.L., Grosshans, R., 2006. Nutrient removal and bio-energy production from Netley-Libau Marsh at Lake Winnipeg through annual biomass harvesting. Biomass Bioenergy 30, 529–536.

Cris, R., Buckmaster, S., Bain, C., Reed, M. (Eds.), 2014. Global peatland restoration demonstrating success. IUCN UK National Committee Peatland Programme, Edinburgh, 64 pp http://www.iucn-uk-peatlandprogramme.org/sites/www.iucn-uk-peatlandprogramme.org/files/IUCNGlobalSuccessApril2014.pdf.

Daatselaar C., Hoogendam K., Poppe K., 2009. De economie van het veenrietweidebedrijf. Een quickscan voor West-Nederland [The economics of reed cultivation on peat soils—an overview for the Western Netherlands]. InovatieNetwerk Report No. 09.2.218, Utrecht, 61 pp.

EU, 2013. Decision no 529/2013/EU of the European parliament and of the council of 21 May 2013 on accounting rules on greenhouse gas emissions and removals resulting from activities relating to land use, land-use change and forestry and on information concerning actions relating to those activities.

Engloner, A.I., 2009. Structure, growth dynamics and biomass of reed (*Phragmites australis*)—A review. Flora— Morphol. Distrib. Funct. Ecol. Plants 204 (5), 331–346.

Escutia-Lara, Y., Lara-Cabrera, S., Gomez-Romero, M., Lindig-Cisneros, R., 2012. Common reed (*Phragmites australis*) harvest as a control method in a Neotropical wetland in Western Mexico. Hidrobiológica 22 (2), 125–131.

Fredriksson, H., 2002. Storskalig sommarskörd av vass –energiåtgång, kostnader och flöden av växtnäring för system med skörd och efterföljande behandling [Harvesting of common reed during summer—energy consumption, costs and nutrient flow for systems including harvesting and treatment]. Examensarbete, Sveriges lantbruksuniversitet. Institutionen för lantbruksteknik., pp. 92.

Grandiek N., J. van Herk, C. Cronenberg, 2007. De introductie van de rieteconomie. Een duurzaam perspectief voor de Nederlandse veenweidegebieden [The introduction of the reed economy: A sustainable perspective for the Dutch peatlands] InnovatieNetwerk Report No.: 07.2.155, Utrecht, 88 pp.

Groot, R., de, Stuip, M., Finlayson, M., Davidson, N., 2006. Valuing Wetlands: Guidance for valuing the benefits derived from wetland ecosystem services. Ramsar Technical Report No. 3, Ramsar Convention Secretariat, Gland, 46 pp. http://www.ramsar.org/sites/default/files/documents/pdf/lib/lib_rtr03.pdf.

Grosshans, R., Grieger, L., 2015. Cattail Biomass to Energy: Commercial-scale harvesting of cattail biomass for biocarbon and solid fuel. iisd report March 2013, 32 pp. https://www.iisd.org/sites/default/files/publications/cattail-biomass-to-energy-commercial-scale-harvesting-solid-fuel.pdf.

Grosshans, R., Grieger, L., Ackermann, J., Gauthier, S., Swystun, K., Gass, P., Roy, D., 2015. Cattail Biomass in a Watershed-Based Bioeconomy: Commercial-scale harvesting and processing for nutrient capture, biocarbon and high-value bioproducts. iisd report March 2014, 39 pp. https://www.iisd.org/sites/default/files/publications/cattail-biomass-watershed-based-bioeconomy-commerical-scale-harvesting.pdf.

Günther, A., Huth, V., Jurasinski, G., Glatzel, S., 2014. The effect of biomass harvesting on greenhouse gas emissions from a rewetted temperate fen. GCB Bioenergy, http://dx.doi.org/10.1111/gcbb.12214.

Hansson, P.-A., Fredriksson, H., 2004. Use of summer harvested common reed (*Phragmites australis*) as nutrient source for organic crop production in Sweden Agriculture. Ecosyst. Environ. 102 (3), 365–375.

Hardaker, J.B., Huirne, R.B.M., Anderson, J.R., Lien, G., 2004. Stochastic simulation, In: Hardaker, J.B., Huirne, R.B.M., Anderson, J.R., Lien, G. (Eds.) Coping with Riskin Agriculture, 2nd ed. CABI Pub., Wallingford, Oxfordshire, Cambridge, MA,pp. 157–181, http://dx.doi.org/10.1079/9780851998312.0157.
Haslam, S.M., 2010. A Book of Reed: (*Phragmites australis* (Cav.) Trin. Ex Steudel, Phragmites Communis Trin.). Forrest Text, Cardigan, 254 pp.
Hawke, C.J., José, P.V., 1996. Reedbed Management for Commercial and Wildlife Interests. The Royal Society for the Protection of Birds, Sandy, 212 pp.
Ikonen, I., Hagelberg, E. (Eds.), 2007. Read up on Reed!. Southwest Finland Regional Environment Centre, Turku, Finland, 125 pp.
IPCC (Intergovernmental Panel on Climate Change), 2014. 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J. Fukuda, M., Troxler, T.G. (eds). IPCC, Switzerland, 354 pp.
Jakubowski, A.R., Casler, M.D., Jackson, R.D., 2010. The benefits of harvesting wetland invaders for cellulosic biofuel: an ecosystem services perspective. Restor. Ecol. 18 (6), 789–795.
Jong, J.J., de, Schaafsma, A.H., Aertsen, E.J.M. and Hoksbergen, F. Th, 2003. Machines voor het beheer van natte graslanden. Een studien aar de kosten van beheer van natte en vochtige graslanden met aangepaste machines. Alterra-rapport 747, Wageningen, Alterra, Research Instituut voor de Groene Ruimte, 45 pp.
Joosten, H., Clarke, D., 2002 Wise use of mires and peatlands—Background and principles including a framework for decision-making. International Mire Conservation Group/International Peat Society, 304 pp.
Joosten, H., Tapio-Biström, M.-L., Tol, S. (Eds.), 2012. Peatlands—guidance for climate change mitigation by conservation, rehabilitation and sustainable use. Mitigation of Climate Change in Agriculture Series 5. FAO, Rome, 100 pp http://www.siagua.org/sites/default/files/documentos/an762e_0.pdf.
Joosten, H., Brust, K., Couwenberg, J., Gerner, A., Holsten, B., Permien, T., Schäfer, A., Tanneberger, F., Trepel, M., Wahren, A., 2015. MoorFutures® Integration of additional ecosystem services (including biodiversity) into carbon credits-standard, methodology and transferability to other regions. BfN Skript 407. Bundesamt für Naturschutz (Federal Agency for Nature Conservation), Bonn, pp. 119.
Kask, Ü., (ed.), 2013. Guidebook of reed business. Report from the project COFREEN—Reed for Bioenergy and Construction, Talinn University of Technology, 109 pp.
Kitzler, H., Pfeifer, C., Hofbauer, H., 2012. Combustion of reeds in a 3 MW district heating plant. Int. J. Environ. Sci. Dev. 3 (4), 407–411, http://dx.doi.org/10.7763/IJESD.2012.V3.256.
Knox, S.H., Sturtevant, C., Matthes, J.H., Koteen, L., Verfaillie, J., Baldocchi, D., 2015. Agricultural peatland restoration: effects of land-use change on greenhouse gas (CO_2 and CH_4) fluxes in the Sacramento-San Joaquin Delta. Global Change Biol. 21 (2), 750–765, http://dx.doi.org/10.1111/gcb.12745.
Köbbing, J.F., Thevs, N., Zerbe, S., 2013. The utilisation of reed (*Phragmites australis*): a review. Mires Peat 13, 1–14 http://mires-and-peat.net/media/map13/map_13_01.pdf.
Köbbing, J.F., Patuzzi, F., Baratieri, M., Beckmann, V., Thevs, N., Zerbe, S., 2014. Economic evaluation of common reed potential for energy production: a case study in Wuliangsuhai Lake (Inner Mongolia, China). Biomass Bioenergy 70, 315–329, http://dx.doi.org/10.1016/j.biombioe.2014.08.002.
Komulainen, M., Simi, P., Hagelberg, E., Ikonen, I., Lyytinen, S., 2008. Reed Energy—Possibilities of Using the Common Reed for Energy Generation in Southern Finland. Turku University of Applied Sciences reports 67, Turku, 81 pp.
Kotowski, W., Jabłońska, E., Bartoszuk, H., 2013. Conservation management in fens: do large tracked mowers impact functional plant diversity? Biol. Conserv. 167, 292–297.
Kresovich, S., Wagner, C.K., Scantland, D.A., Lawhon, W.T., 1981. Emergent aquatic plants: biological and economic perspectives. Biomass 1 (2), 127–144.
Kuhlman, T., Diogo, V., Koomen, E., 2013. Exploring the potential of reed as a bioenergy crop in the Netherlands. Biomass Bioenergy 55, 41–52.
Lachmann, L., Marczakiewicz, P., Grzywaczewski, G., 2010. Protecting Aquatic Warblers (*Acrocephalus paludicola*) through a landscape-scale solution for the management of fen peat meadows in Poland. Grassland Science in Europe 15, 711–713.
Lishawa, S.C., Lawrence, B.A., Albert, D.A., Tuchman, N.C., 2015. Biomass harvest of invasive *Typha* promotes plant diversity in a Great Lakes coastal wetland. Restor. Ecol., http://dx.doi.org/10.1111/rec.12167.
Liu, D., Wu, X., Chang, J., Gu, B., Min, Y., Ge, Y., Shi, Y., Xue, H., Peng, C., Wu, J., 2012. Constructed wetlands as biofuel production systems. Nat. Clim. Change 2 (3), 190–194.
Luthardt, V., Wichmann, S., 2016. Ecosystem services of peatlands, in: Wichtmann, W., Schröder, C., Joosten, H. (Eds.), Paludiculture—cultivation of wet peatlands. Climate protection, biodiversity, regional economic benefits. Schweizerbart Science Publishers, in press.
Maltby, E., 1986. Waterlogged wealth. Why Waste the World's Wet Places? Earthscan, London, pp. 200.
Meerburg, B.G., Vereijken, P.H., Visser, W., Verhagen, J., Korevaar, H., Querner, E.P., Blaeij, A.T., Werf, A., 2010. Surface water sanitation and biomass production in a large constructed wetland in the Netherlands. Wetlands Ecol. Manage. 18 (4), 463–470.
Middleton, B.A., Holsten, B., van Diggelen, R., 2006. Biodiversity management of fens and fen meadows by grazing, cutting and burning. Appl. Veg. Sci. 9 (2), 307–316.
Morton, J.F., Snyder, G.H., 1976. Aquatic crops vs organic soil subsidence. Proc. Fla. State Hortic. Soc. 89, 125–129.
Palisade, 2013. Users Guide @RISK. Risk Analysis and Simulation Add-In for Microsoft ® ExcelVersion 6. 914 pp.
Polman, N., Blaeij, A., van der Heide, M., Linderhof, V., Reinhard, S., 2014. Valuation of ecosystem services provided by man-made wetlands. In: Nunes, P., Kumar, P., Dedeurwaerdere, T. (Eds.), Handbook of the Economics of Ecosystem Services and Biodiversity. Edward Elgar, Cheltenham, UK; Northampton, MA, USA, pp. 454–465.
Porter, P.S., Snyder, G.H., Deren, C.W., 1992. Flood-Tolerant crops for low input sustainable agriculture in the everglades agricultural area. J. Sustain. Agric. 2 (1), 77–101.
Regina, K., Budiman, A., Greve, M.H., Grønlund, A., Kasimir, Å., Lehtonen, H., Petersen, S.O., Smith, P., Wösten, H., 2015. GHG mitigation of agricultural peatlands requires coherent policies. Clim. Policy, http://dx.doi.org/10.1080/14693062.2015.1022854.
Rösch, C., Skarka, J., Raab, K., Stelzer, V., 2009. Energy production from grassland—assessing the sustainability of different process chains under German conditions. Biomass Bioenergy 33 (4), 689–700, http://dx.doi.org/10.1016/j.biombioe.2008.10.008.
Rawlins, A., Morris, J., 2010. Social and economic aspects of peatland management in Northern Europe, with particular reference to the English case. Geoderma 154, 242–251.
Rodewald-Rudescu, L., 1974. Das Schilfrohr. Die Binnengewässer, vol. 27. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, pp. 302.
Schäfer, A., 2004. Umwelt als knappes Gut–Ökonomische Aspekte von Niedermoorrenaturierung und Gewässerschutz. Archiv f. Naturschutz und Landschaftsforschung 43, 87–105.
Schaller, L., Kantelhardt, J., Drösler, M., 2011. Cultivating the climate: socio-economic prospects and consequences of climate-friendly peat land management in Germany. Hydrobiologia 674 (1), 91–104.
Tanneberger, F., Tegetmeyer, C., Dylawerski, M., Flade, M., Joosten, H., 2009. Commercially cut reed as a new and sustainable habitat for the globally threatened Aquatic Warbler. Biodivers. Conserv. 18 (6), 1475–1489.
Toet, S., Bouwman, M., Cevaal, A., Verhoeven, J.T., 2005. Nutrient removal through autumn harvest of phragmites australis and thypha latifolia shoots in relation to nutrient loading in a wetland system used for polishing sewage treatment plant effluent. J. Environ. Sci. Health Part A 40 (6–7), 1133–1156.
Turner, K., Georgiou, S., Fisher, B., 2008. Valuing ecosystem services. The case of multi-functional wetlands. Earthscan, London, pp. 229.
Valkama, E., Lyytinen, S., Koricheva, J., 2008. The impact of reed management on wildlife: a meta-analytical review of European studies. Biol. Conserv. 141 (2), 364–374.
Verhoeven, J.T.A., Setter, T.L., 2009. Agricultural use of wetlands: opportunities and limitations. Ann. Bot. 105 (1), 155–163, http://dx.doi.org/10.1093/aob/mcp172.
Vymazal, J., 2005. Removal of nitrogen via harvesting of emergent vegetation in constructed wetlands for wastewater treatment. In: Vymazal, J. (Ed.), Natural and Constructed Wetlands: Nutrients, Metals and Management. Backhuys Publishers, Leiden, The Netherlands, pp. 209–221.
Wichmann, S., Köbbing, J., 2015. Common reed for thatching—a first review of the European market. Ind. Crop. Prod., http://dx.doi.org/10.1016/j.indcrop.2015.09.027.
Wichmann, S., Dettmann, S., Dahms, T., 2016. Agricultural machinery for wet areas. In: Wichtmann, W., Schröder, C., Joosten, H. (Eds.), Paludiculture—cultivation of wet peatlands. Climate protection, biodiversity, regional economic benefits. Schweizerbart Science Publishers, in press.
Wichtmann, W., Joosten, H., 2007. Paludiculture: peat formation and renewable resources from rewetted peatlands, Newsletter of the International Mire Conservation Group, 3/2007, 24–28.
Wichtmann, W., Schäfer, A., 2007. Alternative management options for degraded fens: utilisation of biomass from rewetted peatlands. In: Okruszko, T., Maltby, E., Szatylowicz, J., Swiatek, D., Kotowski, W. (Eds.), Wetlands: Monitoring, Modelling and Management. Taylor and Francis, pp. 273–279.
Wichtmann, W., Tanneberger, F., 2011. Land use options for rewetted peatlands. In: Tanneberger, F., Wichtmann, W. (Eds.), Carbon Credits from Peatland Rewetting. Climate – Biodiversity – Land Use. Science, Policy, Implementation and Recommendations of a Pilot Project in Belarus. Schweizerbart, Stuttgart, pp. 107–132.
Wichtmann, W., Wichmann, S., 2011. Environmental, social and economic aspects of a sustainable biomass production. J. Sustain. Energy Environ., 77–81 (special issue).

Paper II

Wichmann, S. & Köbbing, J. F. (2015)

Common reed for thatching—A first review of the European market.

Industrial Crops and Products 77: 1063–1073.

Industrial Crops and Products 77 (2015) 1063–1073

Contents lists available at ScienceDirect

Industrial Crops and Products

journal homepage: www.elsevier.com/locate/indcrop

Common reed for thatching—A first review of the European market

Sabine Wichmann*, Jan Felix Köbbing

Institute of Botany and Landscape Ecology, Division of Landscape Economics, University of Greifswald, Soldmannstraße 15, 17487 Greifswald, Germany

ARTICLE INFO

Article history:
Received 27 April 2015
Received in revised form 3 September 2015
Accepted 12 September 2015

Keywords:
Roofing
Phragmites australis
Wetland use
Paludiculture

ABSTRACT

Common reed is a globally distributed wetland plant that has been used by humans for centuries with a wide range of applications. Until today, reed as roofing material is the most common use in Europe. However, large reed areas in Western Europe were lost for harvesting during the 20th century due to extensive industrial meliorations of wetlands on the one hand and the protection of remaining reed habitats on the other hand. This paper investigates the changes in the European market for thatching reed based on surveys among stakeholders, analysis of trade statistics, and extensive literature research. Analysing total consumption, imports and exports since 1990 revealed a discrepancy between consuming and producing countries. Western Europe, mainly the Netherlands, Germany, UK, and Denmark, relies on imports of up to 85% of the national consumption. This reed demand became primarily covered by large wetlands in Eastern and Southern Europe, e.g. Hungary, Poland, Romania, Turkey, and Ukraine; since 2005, reed from China accounts for a considerable share of the European market. At the same time, recent year's efforts to rewet and restore drained wetlands in Western Europe increased the reed growing area and—if quality requirements are met and harvesting is allowed—can improve the national availability of thatching reed.

1. Introduction

1.1. Common reed—a world wide spread plant with multiple applications

Common Reed (*Phragmites australis* (Cav.) Trin. ex Steud.), from this point onward 'reed', is a tall, thin, highly productive grass that can be found in wetlands all around the world (except in the Antarctica), but is mostly distributed in Europe and the Middle East (Haslam, 2010). Reed has a long history as a plant used by humans. Well known are the Marsh Arabs from Euphrates and Tigris, whose wetland adapted culture is presumed to be 5,000 years old (Thesinger, 2007), or the extensive reed utilisation in the Danube Delta (Rodewald-Rudescu, 1974) and in South Africa (Tarr et al., 2004).

Where reed was common it was used for a wide range of applications encompassing agriculture (fodder or litter), construction purposes (roofing, walls, panels, fish traps etc.), horticulture (mats protecting against wind or frost, fences), industry (pulp and paper) or energy generation (combustion) (cf. Haslam, 2010; Köbbing et al., 2013; Rodewald-Rudescu, 1974; Thevs et al., 2007; Wichtmann, 1999). Nowadays, the most common utilisation of reed in Europe is thatching.

1.2. Plant material for thatching

From Neolithic times, thatching of roofs traditionally relied on the locally available plant material as reed and sedges in wetlands, straw in arable regions or heather in the Scottish Highlands (Haslam, 2010). Reed as thatching material has a history of thousands of years starting with humans becoming sedentary and lasting until today. The importance of straw as cheap, abundant, and easily available thatching material (Moir and Letts, 1999) was limited to a shorter period. Cereal straw played a major role for about 500 years, beginning with the appearance of the scythe in Europe around 1500, allowing the harvest of long stalks suitable for thatching, and lasting until mechanical threshing machines replaced manual harvest in the second half of 19th century (Schrader, 1998). An even shorter period of two to three generations, that started only when the introduction of mineral fertilizer improved the available quantity of straw as well as length and strength of stalks, is stated by Schattke (1992). While mainly wheat straw was used in the UK, rye straw was common for instance in Estonia and Germany (Moir and Letts, 1999; Schrader, 1998). Straw and reed appeared to be the only roofing material available until the late 1800s in European countryside, when it was steadily replaced by other materials, but remained common until the 1960s for example in Estonia (Iital et al., 2012;

* Corresponding author.
E-mail address: wichmann@uni-greifswald.de (S. Wichmann).

http://dx.doi.org/10.1016/j.indcrop.2015.09.027

Lautkankare, 2007). The availability of tiles and slates, improved by the introduction of railway transport, enabled the banning of thatched roofs because of fire risk especially in towns (Haslam, 2010). Consequently, straw and reed became despised as roofing material for poor rural areas.

The return to natural building materials and life in the countryside enhanced the reputation of thatched roofs being even considered as luxury due to high costs for roofing and insurance (Haslam, 2010; Schrader, 1998). Nowadays, reed is usually preferred to straw as thatching material because of its better availability and the longer durability of the thatched roofs with 50–60 years for common reed (Rural Development Commission, 1988).

1.3. Reed beds in Europe

In the 20th century, Europe's wetland area declined significantly and thereby the reed beds to harvest: Around two-thirds of European wetlands were lost from the beginning of last century until 1995 (EC, 1995). In the Netherlands, France, Germany, Spain, Italy, and Greece more than 55% of wetlands were lost between 1950 and 1985; Lithuania and Sweden experienced an even higher decline (Silva et al., 2007). Reasons for the loss were the intensified drainage for agriculture, river regulations, water overexploitation, and pollution. For reed beds, a phenomena called "die-back" has been observed since the 1950s which is connected to eutrophication and changing water regimes (Van der Putten, 1997).

The recognition of the manifold benefits of wetlands (e.g. Millennium Ecosystem Assessment, 2005) fostered the protection of remaining areas, but also attempts at sustainable utilisation. Those aims include the combination of reed bed restoration and management for conservation objectives (Hawke and Jose, 1996), the introduction of paludiculture as a land use alternative for rewetted peatlands encompassing the cultivation of reed for thatching (Wichmann, 2016; Wichtmann and Schäfer, 2007) or (re-)discovering extended reed beds, e.g. along the coast of the Baltic Sea, to meet the increasing demand for renewable resources (Ikonen and Hagelberg, 2007; Kask, 2013). However, biomass harvest and utilisation in general are allowed only for parts of the remaining or restored wetlands. Additionally, the share of reed beds suitable for delivering high quality thatching material is unknown.

1.4. Purpose of the paper

Considering the lack of knowledge about the potential supply of thatching reed, this paper investigates the European demand and how it is met. Even if reed is almost exclusively used for thatching in Europe, almost nothing has been known so far about the market situation. Where are the consumer countries, where are the suppliers? How did it change over recent years? What are the purchasing prices? Based on surveys, trade statistics, and literature data this paper provides an overview about the market situation in Europe.

2. Material and methods

To picture the European reed market as comprehensive as possible, a triangulation of methods was applied. While expert interviews allowed to elicit data on prices and personal insights in changing national demand, the analysis of trade statistics delivered objective data backing up the information on volumes exported or imported and changes over time. The literature review contributed data being especially valuable for cross checking information originating from different time periods.

2.1. Surveys

A short, semi-structured questionnaire was sent out to European reed producers, traders, thatchers, and umbrella organisations via mail in May and June 2013. Where necessary, it was followed by a reminder in August 2013 offering a phone call as alternative to a written reply. Therefore, in some cases the survey was conducted on the phone with the questionnaire being used as an interview guide. The questionnaire combined closed and open questions leaving also space for further comments. The questions aimed at identifying countries important for the reed market (traditions in thatching, importer or exporter), consumption of reed and share of domestic production in the home country and in Europe since 1990, changes over time in volumes and end consumer prices for the major exporter and importer as well as reasons for it.

In addition to contacting already known experts from the reed sector and associations as the International Thatching Society, all interviewees were asked to recommend further experts to include in the survey (snowball effect). Responses according to interview group and country are shown in Table 1. The 14 interviews were anonymised and are referred to as interview partner (IP) 1-14.

2.2. Trade statistics

The statistical database of Eurostat, a Directorate-General of the European Commission (EC, 2011), was used for analysing mass flows for the major import and export countries for the period from 1990 to 2012. Imported and exported goods in the European Community have to be classified according to the Combined Nomenclature, an 8-digit code. Thatching reed bundles are grouped in the commodity group '1401 90 00', together with other 'Vegetable materials of a kind used primarily for plaiting' including also rushes, osier, raffia, cleaned, bleached or dyed cereal straw, and lime bark (EC, 2011). The share of reed in the product category is unknown, but the trade of plaiting material as raffia between the considered countries is assumed to be negligible. Additionally, the statistical data are given in kilograms, but the reed is traded in bundles of varying length and weight. Out of these two reasons we abstained from a conversion of the traded volume from weight into bundles and used the statistical data mainly to illustrate trends over time.

2.3. Literature

The in-depth literature research was based on available English, German, and Dutch references, which necessarily lead to a better data basis for the corresponding countries than for others also relevant for reed demand and supply. The analysis included books, peer-reviewed, and grey literature as well as web sources. In gen-

Table 1
Number of answers received from different reed stakeholders ordered according to countries (multiple answers were possible for group affiliation).

Groups	Country							Total
	Austria	Denmark	Germany	Hungary	Netherlands	Poland	UK	
Producer	1	–	1	1	2	1	–	6
Trader	1	–	1	–	2	–	–	4
Thatcher	–	–	2	–	–	1	1	4
Umbrella association	–	1	1	–	1	–	3	6
Total	1	1	4	1	2	1	4	14

eral, the available data are widely scattered and sometimes difficult to access (e.g. grey literature). Some information could be extracted from thatching instructions and official publications of thatching associations. Peer-reviewed literature mainly focuses on ecologic and biodiversity aspects of reed beds and their management. No comprehensive and quantitative overview on the European market exists so far.

3. Results and discussion

3.1. Market requirements for thatching reed

For high quality thatching reed straight, thin, flexible, and firm culms of one-year-old stands are used, cut off just above the base since the butt is the most durable part influencing the life span of the roof (Haslam, 2009). A moisture content of 18% at most is ensured by winter harvest of reed stands that were naturally dried by frost, wind and sun after dying off. Old and short stems as well as other leftovers (e.g. other plants) have to be removed and can make up to 50% of the standing biomass. Using poor quality reed is one of several reasons causing premature decay of thatched roofs (Wykes, 2010).

Reed for thatching is traded as bundles. The size of a reed standard bundle varies from country to country (Table 2). The usual circumference is 60 cm ('Euro bundle'), while in the Netherlands 55 cm are common. Stem diameter is ≤6, 3–9 and 6–12 mm for short, medium, and long reed in Germany, respectively (QSR, 2008). UK distinguishes in fine, medium, and coarse reed which is 3.2, 4.8, and >5.6 mm, respectively (BRGA, n.d.; Haslam, 2010), independent from the length of the bundles. Subject to their length (short, middle, long) bundles are suitable for different parts or types of thatched roofs. Depending on productivity, size of bundles and quality 250–1,000 bundles per hectare can be harvested (Schäfer, 1999; White, 2009). A roof of 30 cm thickness requires 10 to 11 bundles (60 cm circumference) per m^2 (Haslam, 2009; Schattke, 1992), thus up to 100 m^2 can be thatched with the yield of one hectare (Schattke, 1992). Depending on bundle size and moisture content, one ton of reed equals to 160–220 bundles (4.2–6.2 kg per bundle) (ELP, 2010).

3.2. Consumption and production by countries

In the survey, the following countries were mentioned as having a tradition in using reed as thatching material (response ≥3 times): Belgium, Denmark, France, Germany, Japan, the Netherlands, Poland, and UK. Infrequently mentioned or inconsistently classified were Austria, Estonia, Hungary, Ireland, Latvia, Lithuania, Luxembourg, Romania, Mesopotamia (Iraq), South Africa, and Sweden.

The thatching reed production in most European countries decreased continuously during the last decades (IP 14). Most countries in Western and Central Europe cannot cover their demand by themselves, but rely on imports from Eastern and Southern Europe and in more recent times China. Thus, the European reed market reflects a discrepancy between consuming and producing countries (see Fig. 1). In the following, the main importing and exporting countries are presented in detail.

3.3. Importing countries

3.3.1. The Netherlands

The Netherlands are well known as water rich country, but also for their precise water regulation to enable drainage and intensive use of formerly extensive wetlands. Consequently, the remaining reed beds are mainly found in protected areas, not being able to meet the demand for traditional thatching material. In the National Park Weeribben-Wieden an area of 2,500 ha is harvested (Terwan and van der Fluit, 2011). Sluis et al. (2013) cite the total reed area in the Netherlands to be 9,000 ha, of which 2,850 ha (30%) is currently harvested. The Netherlands are the largest thatching reed consumer and at the same time the most important hub for reed distribution in Europe. Producing, importing and exporting reed in and out of the Netherlands makes it difficult to determine the domestic reed production and consumption. A continuous increase in reed used for roofing from 4 (1999), to 6.5 (2003), to 8 (2006) and 10 (2007 and 2008) million bundles is stated by IP 1, but not shown properly by the time slots in Table 4. With the financial crisis in 2007 the market declined steadily to 3.5–6 million in 2013 (IP 6; IP 10). Consequently, the import share decreased from 80 to 70% (Table 4) while the domestic production was stable at around 2 million bundles in the last 20 years (IP 1; IP 6). The amount of 6 to 7 million bundles, as cited by Lautkankare (2007), seems to be too high and close to the total consumption. So far, the Dutch reed market has not recovered from the crisis fully and a reduced consumption of 5 to 6 million bundles is projected for the future (IP 6).

In the period since 1990, the main countries exporting to the Netherlands have been Austria, Germany, Hungary, Romania, Turkey, Ukraine, and China (since 2005) (IP 10; Fig. 2). Of minor importance for delivering reed to the Netherlands have been Denmark (IP 10), France (IP 6; IP 10), Luxembourg (IP 6), and the Baltic countries (IP 10). For part of the imports (e.g. from China) the Netherlands might be only a transit country exporting to other European countries such as Germany, Belgium, and especially in the first half of the 1990s the UK (Fig. 2h). 3 to 4 million bundles per year are assumed to pass through the Netherlands (IP 1).

The Dutch reed business is very innovative, using reed not only for traditional thatching of private houses and whole holiday estates but also in a contemporary building-design and structure (e.g. vertical thatching), and also invests in promoting the craft of thatching with the help of "The Federation of Reed Thatcher's" (Wykes, 2010).

Table 2
Dimensions of reed standard bundles as common in selected countries (circumference measured at the point of tie).

Country	Short		Middle		Long	
	Circumference [cm]	Length [m]	Circumference [cm]	Length [m]	Circumference [cm]	Length[m]
Germany[a]	60	1–1.5[e]	60	1.6–1.8[e]	60	1.9–2.3[e]
UK[b,c]	60	0.9–1.2	60	1.2–1.7	<60	>1.7[f]
Netherlands[d]	55	1.0–1.2	55	1.4–1.8	55	1.9–2.1

[a] (QSR, 2008).
[b] (BRGA, n.d.).
[c] Haslam, (2010).
[d] IP 14
[e] At least 2/3 of stems with the given length.
[f] Reed >2 m should be notified to the buyer.

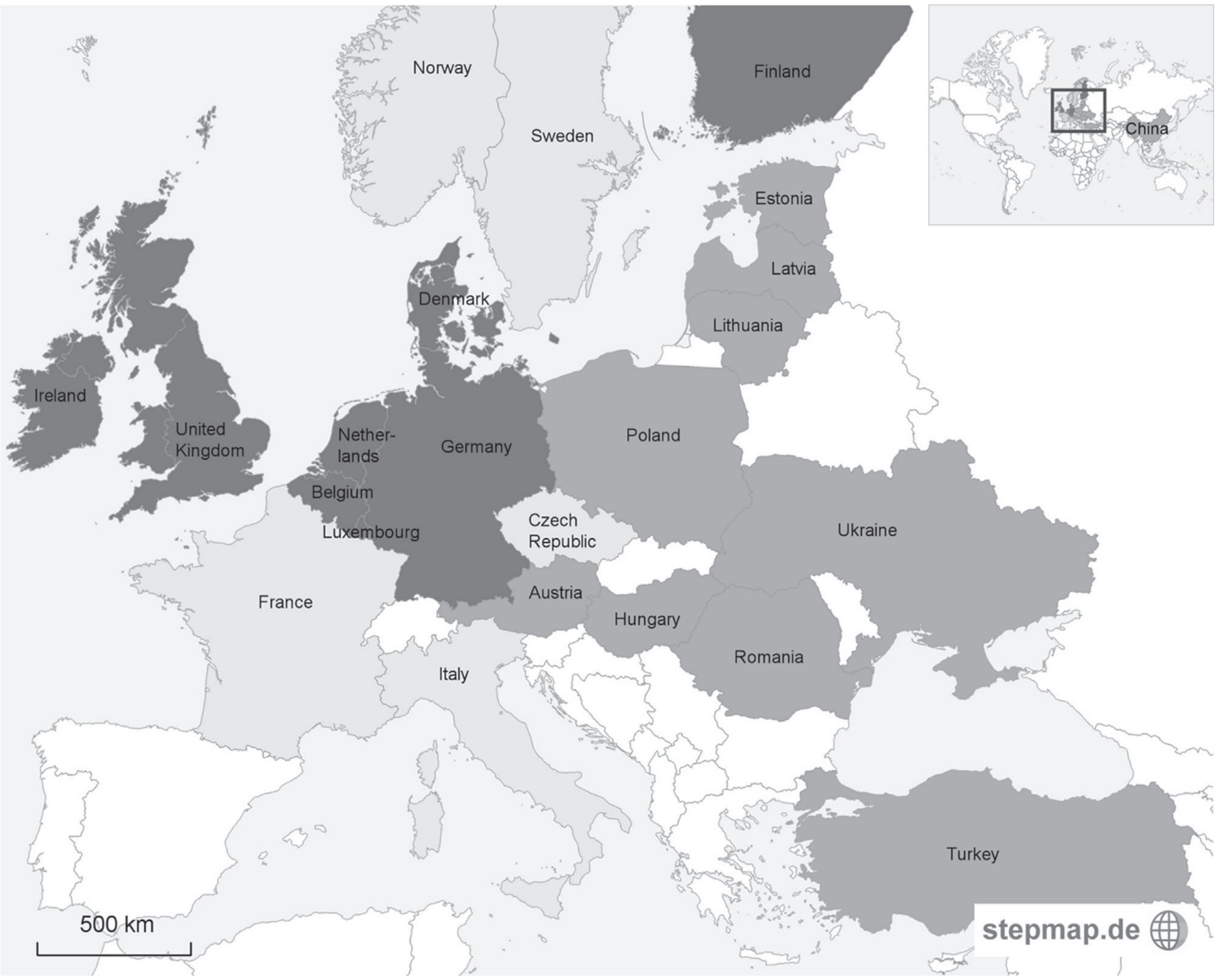

Fig. 1. European countries predominantly importing (dark grey) and exporting (medium grey) thatching reed, or being neutral (light grey). The world map additionally shows China as major reed supplier for the European market.

3.3.2. Germany

Germany has a long tradition in reed thatching. The consumption and production areas are mainly located in the Northern federal states Lower-Saxony, Schleswig-Holstein, Mecklenburg-Western Pomerania, and Brandenburg that are characterised by their long coastline of the North and Baltic Sea, or a richness of inland lakes. However, high land use competition, nature and bird protection reducing the harvested area, increasing labour costs, and cheap thatching alternatives has led to a lack of domestically produced reed (IP 1; Ritterbusch, 2011). The cut reed area in Mecklenburg-Western Pomerania was stated to be 1,500 ha (Schäfer, 1999). Schleswig-Holstein is supposed to have a significant bigger area whereas the commercially cut reed area in Brandenburg is of no significance nowadays (Ritterbusch, 2011). For the period 1990–2013 the total consumption alternates around 3 million bundles and the import share around 80% (Table 4). The amount of indigenous reed seems to decrease but the basis of data is too weak to come to a final conclusion.

Hungary, Turkey, and Poland were named as important reed supplier for Germany before 1999, in the following years Romania increased and the Ukraine gained importance (IP 1; IP 12; see also Fig. 2b,e). Since 2005 imports from China (IP 1; IP 12; Fig. 2c) steadily filled up the gaps caused by the reduced amount obtained from traditional export countries as Hungary (Fig. 2a).

The estimated German imports by countries (Table 3) are based on two references with IP 1 citing conservative values, compared to rough and rounded numbers from IP 12. A total import volume of 2 million bundles seems therefore more realistic and in line with the total consumption in Table 4.

3.3.3. United Kingdom

The United Kingdom (UK) is widely recognized as a traditional reed thatching country by interviewees, which is also confirmed in

Table 3
Countries exporting to Germany with specific amounts of reed and end consumer prices in 2013.

		Austria	China	Hungary	Poland	Romania	Turkey	Ukraine	Total
Export volume	Million bundles	0.1[a]	0.2[a]–1[b]	0.6[a]–2[b]	0.1[a]–1[b]	0.4[a]–1[b]	0.3[a]–1[b]	0.3[a]–1[b]	2–7
Price	€	n.d.	Variable[a]	2.60[a]	2.60[a]	3.00[a]	2.40[b]- 3.00[a]	2.80[a]	n.a.

[a] IP 1.
[b] IP 12.

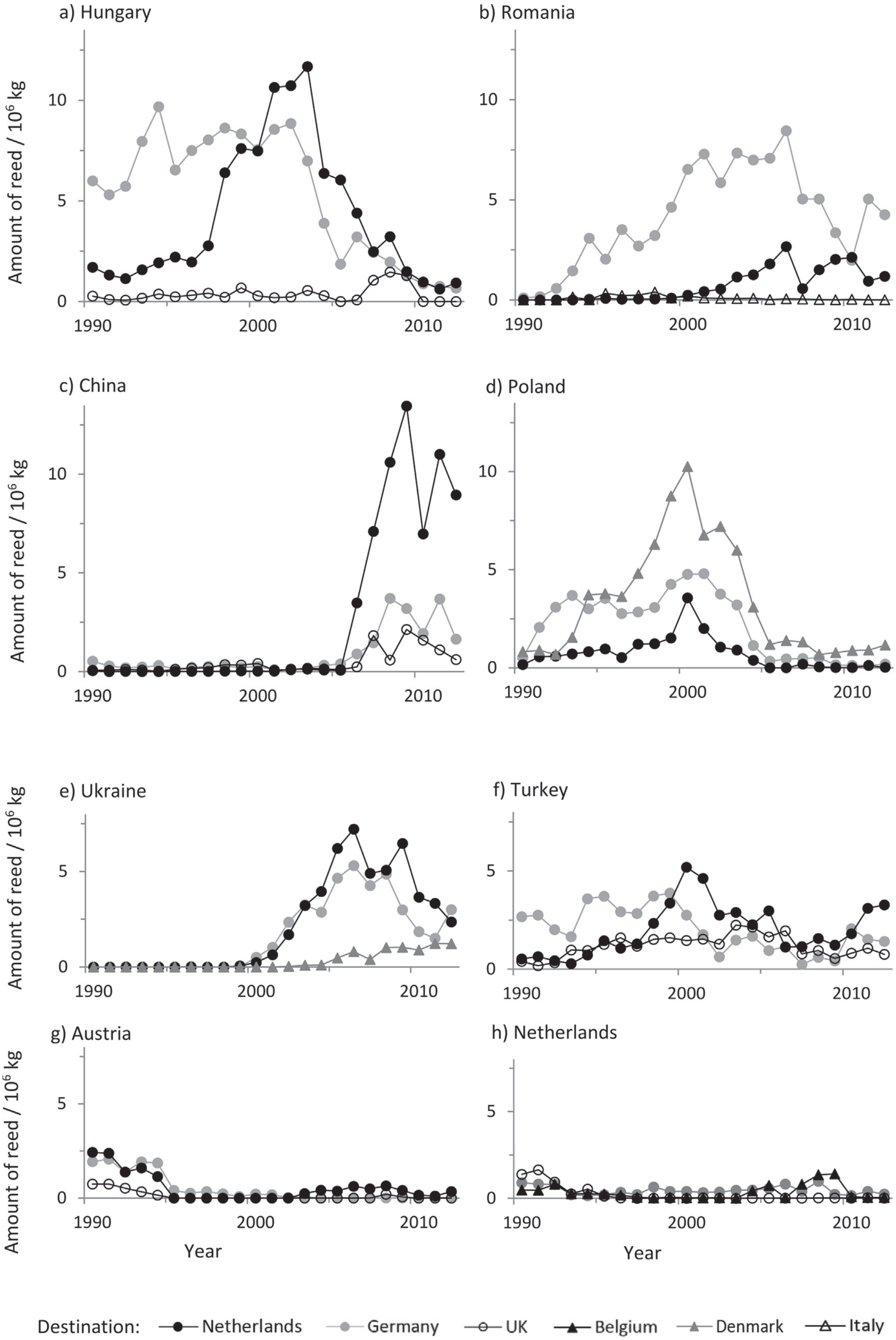

Fig. 2. Annual reed exports from countries being of major importance (a) Hungary, b) Romania, c) China, d) Poland) and of moderate importance (e) Ukraine, f) Turkey, g) Austria and h) the Netherlands), each with the three most relevant consuming countries (trade statistic data from Eurostat, product category includes also rush, basket willow, raffia).

the literature (Cox and Letts, 2000; Moir and Letts, 1999). In general, cereal straw and reed were used according to local availability and the straw roofing is assumed to be used since more than 3,000 years (Cox and Letts, 2000). The new short-stem straw varieties introduced in the 1960s were unsuitable for thatching and reed became more used. However, the growing reed market could not be satisfied with indigenous reed alone. While small quantities of reed were imported via the Netherlands as early as in the 1930s, the demand to supplement domestic reed production has been increasing steadily over the decades (Cox and Letts, 2000). Reasons for the higher dependence on imports has been different like the war intensifying shortage, reed being used in paper production, difficulties to find workers for the hard work of manual reed harvest, and the conservation of wildlife reducing the area allowed for cutting (Cox and Letts, 2000).

The domestic reed area in 1960 was suitable for thatching only 150 standard cottages per year (Moir and Letts, 1999). It was estimated that 10–40% of reed beds had been lost between 1945 and 1990 (Kent Wildlife Trust, 2005). According to an inventory of British reed beds in 1993 c. 5,000 ha remained (Painter et al., 1995) from which c. 65% were cut for thatching reed every or every second year (Bateman et al., 1991) (both sources cited in Boar et al., 1999). Considering the importance of reed beds as breeding and feeding habitat for rare bird species, an initiative started in the 1990s that aimed at increasing the reed area by 1,200 ha and rehabilitating a further 800 ha reaching a target area of 6,500 ha of managed reed beds in 2010 (Dickie, 2001; White, 2009). The majority of UK reed beds are very small and fragmented in comparison to those in other countries as the Netherlands (Hawke and Jose, 1996). The largest producer of British thatching reed in the year 1986 was situated in Scotland with around 0.1 million bundles per year (Haslam, 1989), today it is the Tay estuary with a reed area of >600 ha (Alsbury, 2010). Well-known other reed sites are the Norfolk Broads and East Anglian reed beds. According to White (2009) 2,000 ha of additional reed beds would be necessary to cover the domestic demand with indigenous reed.

The overview about the present reed market in the UK (Table 4) shows clearly the high dependency on imports, which cover 75% of the demand today. High labour costs and nature conservation policy limit the availability of thatching reed in the UK (Dickie, 2001; IP 5). The simultaneous increase in demand has intensified the dependency on imports additionally over the last decades (Dickie, 2001; White, 2009; IP 5). However, the share of domestic produced reed had increased slightly to 25% (Broads Authority, 2012). A total consumption of 0.34 million bundles in 2013 (IP 8) seems to be very low and may be misinterpreted by

Table 4
Total consumption, domestic production, import share and end consumer prices in the Netherlands, Germany, United Kingdom and Denmark, as countries having a high demand for thatching reed, for the period 1990–2025.

Country	Period	Total consumption	Domestic production	Import share	Price	Price, adjusted[w]
		Million bundles	Million bundles	%	€	€(2013)
Netherlands	1990–1998	10[a]	n.d.	50[a]	n.d.	n.d.
	1999–2007	4[a,c]–10[b]	(6–7[d])	80[a]	n.d.	n.d.
	2008–2012	6[b]	n.d.	70[a]	2.95[e]	3.00–3.20
	2013	3.5[b]–6[a]	2[a,b]	70[a,b]	2.10[f]	2.10[f]
	2025 (outlook)	5–6[a]	n.d.	85[a]	n.d.	n.d.
Germany	1990–1998	3[g]	n.d.	80[g]	n.d.	n.d.
	1999–2007	3[g,i]–4.8[h]	0.7[h]–1[d]	80–85[h]	n.d.	n.d.
	2008–2012	2[g]–3[b,i]	n.d.	80[g,k]–85[i,j,l]	2.00[e]–2.50[b]	2.20–2.70
	2013	2–3[g]	0.5–0.7[b]	70[k]–80[g]	2.10[f]–3.50[g]	2.10[f]–3.50[g]
	2025 (outlook)	n.d.	n.d.	n.d.	n.d.	n.d.
United Kingdom	1990–1998	1.5[m]	0.35[r]–0.45[q]	75[m]	1.40–1.70[r] (1995)	2.60–3.10
	1999–2007	2[s]	0.2[p]	75[n]	2.00[m]	2.40
	2008–2012	2[s]	0.5[s]	75[n]	2.00[t]–2.50[u]	2.40 –3.00
	2013	(0.34[o])	0.2[p]–0.4[q]	75[o]	n.d.	n.d.
	2025 (outlook)	n.d.	n.d.	80[n]	n.d.	n.d.
Denmark	1990–1998	2.6[v]	n.d.	60[v]	n.d.	n.d.
	1999–2007	3[v]	n.d.	70[v]	n.d.	n.d.
	2008–2012	2.5[v]	(2.5[d])	70[v]	n.d.	n.d.
	2013	1.5[f]–2.5[v]	n.d.	70[v]	2.10[f]–2.50[v]	
	2025 (outlook)	4.5–5[v]	n.d.	75[v]	n.d.	n.d.

[a] IP 6.
[b] IP 1.
[c] IP 10.
[d] (Lautkankare, 2007).
[e] IP 14.
[f] IP 7.
[g] IP 12.
[h] (Schäfer, 1999).
[i] (QSR, 2008).
[j] (Schwarz and Greef, 2011).
[k] IP 11.
[l] (Ritterbusch, 2011).
[m] (Dickie, 2001).
[n] IP 5.
[o] IP 8.
[p] (Yates, 2006).
[q] (George, 1992).
[r] (Hawke and Jose, 1996).
[s] (Broads Authority, 2012).
[t] (White, 2009).
[u] (Alsbury, 2010).
[v] IP 4.
[w] All values converted to € and inflation adjusted (www.fxtop.com) to October 1st, 2013.

the interviewee as the consumption of domestic reed which was between 0.2 and 0.45 million over the last decades (Table 4).

As countries traditionally exporting reed to the UK, the survey identified Austria, Hungary, Poland, Romania, and Turkey; for the period since 2000 also Ukraine and later China (IP 3; IP 8). According to Alsbury (2010) and Haslam (1989) also France and the Netherlands deliver reed to the UK. However, only 20 tons (c. 3,200–4,400 bundles) were imported from the Netherlands in 1999 (Dickie, 2001). The statistical data revealed, that the UK ranks usually third as destination for the exporting countries but concerning the amount is by far less important than the Netherlands and Germany (Fig. 2a,c,f,g).

The interviewees considered the high import share as problematic in terms of environmental impact of transportation from Eastern Europe and China and possible implications for wildlife in intensively managed reed beds in the exporting countries (IP 2). It was also emphasised that the reed business depends on a good reputation and a quality control is highly important (IP 5). Alsbury (2010) highlights that consumers would be willing to pay around 2.50 pounds (in 2010, i.e. 3.00 € in 2013) per bundle for domestic reed which exceeds the price for imported reed by 10–20%.

3.3.4. Denmark

Denmark has 42,000 reed-roofed buildings and the traditional knowledge of thatching has been exported by Danish companies to South Sweden and Norway in recent years (Lautkankare, 2007). Even if Denmark is an important reed thatching country, little information can be found in the English, German, or Dutch literature and no figures could be obtained on the Danish reed areas. IP 4 explained that cereal straw was used until 1975, but the growing demand for reed could not be satisfied by declining Danish reed beds (Ikonen and Hagelberg, 2007). Although rising environmental awareness led to the restoration of wetlands, it depends on environmental regulations if they can be used for reed cutting (IP 4).

According to the total consumption and import share (Table 4), the domestic production was around 0.9 million bundles in 2007. Compared to this number the 2.5 million bundles indigenous reed mentioned by Lautkankare (2008) seem to be too high.

After a comparatively stable total consumption since 1990, a doubling of the demand is expected for the future (Table 4). Denmark has been a major importing country for reed from Poland (IP 7; Fig. 2d). According to statistical data Hungary and Germany have been similar important for delivering reed to Denmark; the Ukraine (since 2005) and to a less extend China (since 2007) gained importance (data not shown).

3.3.5. Other importing countries (alphabetical order)

Belgium is a traditional reed thatching country (Wykes, 2010) and a major destination for reed exports from the Netherlands (Fig. 2h).

Finland has a vast reed area of 100,000 ha according to Pitkänen (2006) cited in Myllyniemi and Virtanen (2013) with 30,000 ha (150,000 tons) located along the south coast and currently unused (Ikonen, 2008; Komulainen et al., 2008). Reed thatched roofs, which were very common in former times, have been widely replaced by new roofing materials (Nordling, 2008; Suna, 2008). An EU financed INTEREG project (2005–2008) tried to reintroduce the reed thatching to Finland by the help of Estonian thatchers and by using the local available reed (Ikonen, 2008; Suna, 2008). However, the reed for the first trials was imported from Estonia and other countries, which shows that no domestic reed is harvested, yet (Lautkankare, 2007; Suna, 2008).

Ireland has a vital reed thatching culture similar to the one in the UK with a total consumption of 0.2 million bundles annually (IP 1). While local reed is rarely available or of poor quality, thatching reed is mostly imported from Turkey and Poland and occasionally from the UK, Hungary, Romania, and Ukraine (Mullane and Oram, 2005).

Luxembourg was named as a traditional reed thatching country (IP 6; IP 14). Due to its size and location it is most likely that most or even all reed is imported.

3.3.6. Summary importing countries

The import share increases for the most important reed consuming countries over the whole investigated period (since the 1990s), continuing also in the future (Table 4). The reasons are a higher demand on the one hand, and on the other hand less supply in Western Europe due to nature protection restricting the harvest, insufficient reed quality caused by a lack of water and by nutrient increase in reed beds, and high harvesting costs.

3.4. Exporting countries

3.4.1. Hungary

Hungary has been providing reed to Western Europe since at least 1967 (Prosman, 2015a). Nowadays, the export volume is 2 million bundles and own consumption is 0.5 million bundles (IP 9). Main export target country is Germany with 0.6–2 million bundles (Table 3) (IP 1; IP 9; IP 12), next to the Netherlands (Fig. 2a) and to a less extent the UK (English Heritage, 2000; Haslam, 2009). The export volume was higher in past years (Fig. 2a) and decreased due to quality problems as well as the closure of small businesses (IP 1). One example is the Hungarian part of Lake Neusiedl, which had a reed growing area of 75 km^2 in 1982 (Knoll, 1986) and has been a major reed supplier, but the amount of harvested bundles decreased from 2 to c. 0.1 million today (IP 14).

3.4.2. China

Reed is exported from China's Northeast, favoured by an access to the sea as well as by cold and very dry winters with 5–6 months of frost (Prosman, 2015b). The export volume to Europe was 2–4 million bundles in 2010 (IP 1; IP 14), but the harvest potential is 40–50 million bundles (IP 14). Therefore, a further increase of the reed exports is very likely (Prosman, 2015b). Germany is receiving 0.2–1 million bundles from China annually (IP 1; IP 12). Interview results, which declared that China has been exporting reed to Germany and the Netherlands since 2005 (Prosman, 2015b; IP 1), are perfectly in line with the statistic data (Fig. 2c). The transportation costs are responsible for 50% of the final selling price, for European reed it would be around 10% (IP 14).

3.4.3. Turkey

Many interviewees named Turkey as an important reed supplier, even if in recent time a reduced water supply of reed beds decreased production (IP 1). The export volume is around 1 million bundles (IP 1), whereof 0.3–1 million bundles go to Germany (IP 1; IP 12). Statistic data show the Netherlands and the UK as important destinations (Fig. 2f). Literature sources confirm that thatching reed is harvested for export, e.g. in the Sultan Marshes (Develi Basin), but also used locally for insulation (Dadaser-Celik et al., 2009).

3.4.4. Romania

The Danube Delta is the largest reed bed of the world with Romania hosting an area of 190,000 ha (DeLaCruz, 1978). At peak production in the year 1964, 226,000 tons were harvested for paper production (Hanganu et al., 2002). Industrial exploitation damaged the reed beds and dropped the production to 125,000 tons in 1976 (National Academy of Sciences, 1976; Rudescu et al., 1965 cited in DeLaCruz, 1978). Today a small part of the reed from the Romanian side of the Danube Delta is harvested for thatching (Hanganu et al., 2002). In 2013, Romania exported 1 million reed bundles, of which

0.4–1 million bundles were shipped to Germany (IP 1; IP 12) and small parts to the Netherlands and Italy (Fig. 2b).

3.4.5. Ukraine

In the Ukrainian part of the Danube Delta 105,055 ha of reed were harvested for paper production during communist times (Rodewald-Rudescu, 1974). After the fall of the Iron Curtain, Ukraine became an important source for thatching reed, e.g. for Germany, the Netherlands, and Denmark (Fig. 2e). Germany received 0.3–1 million bundles in 2013 (IP 1; IP 12). The total export volume was estimated to be 2 million bundles (IP 1).

3.4.6. Poland

Poland is slowly developing a thatching culture. For the total domestic consumption of 0.4 million bundles in 2013, no foreign reed was imported (IP 7). In the Rozwarowo Marshes (NW Poland) more than 1,000 ha of reed are harvested for thatching (Tanneberger et al., 2009). Other commercially cut reed beds are located for instance in East Poland (IP 7). The whole area cut for thatching reed in Poland is estimated to encompass c. 8,000 ha producing c. 1.5 million bundles annually of which approximately 80% are exported (IP 7). Main export countries, in descending order of importance, are Denmark, Germany, the Netherlands and the UK (Fig. 2d). Germany alone received 0.1–1 million bundles in 2013 (IP 1; IP 12).

3.4.7. Austria

Austria is an important export country, even if the export volume is variable and there is only one large reed growing location, which is Lake Neusiedl. The reed area on the Austrian side of Lake Neusiedl was 103 km^2 in 1982, where up to 25 km^2 were traditionally used for reed cutting (Knoll, 1986). By 2010, the harvested area had dropped to 10–15% of the whole reed bed (Führer, 2010). The quality, the yield and the extent of cut reed area are highly variable and depend on weather (e.g. frost) conditions (IP 13; Führer, 2010; Knoll, 1986).

Reed was used locally as fodder, for roofing, and the production of woven reed mats and pressed plates for construction in the past, while demand declined significantly in the 1970s and only recovered slightly in the 1980s and 1990s (Knoll, 1986; Führer, 2010). IP 13 and Führer (2010) highlighted the challenges for the reed business at Lake Neusiedl: traditional harvesters cannot find successors willing to continue the hard work, difficult harvesting conditions, high labour costs, environmental regulations, no political support and high competition from Hungary and China. From 14 reed cutting enterprises in 1990 only three remained in 2013 of which just one was run full time (IP 13). IP 13 concludes that no thatching reed will be harvested at Lake Neusiedl in the medium or long-term. However, foreign reed cutting enterprises have been renting reed areas for harvest, e.g. a company from the Netherlands in 2009 (own observation). The political and research interests have been concentrating on the energy utilisation of the reed resources as an option to manage the large area of old reed stands not cut annually (Führer, 2010; Kitzler et al., 2012).

The up and down of the reed business and a general decline is reflected in the amount of harvested thatching bundles (Table 5).

Table 6
Survey data on domestic consumption, export volume and total production in million bundles in 2013.

Country	Domestic consumption	Export volume	Total production
	Million bundles		
Hungary	0.5[a]	2[a]	2.5
China	n.d.	2[e]-4[c]	>2–4
Turkey	n.d.	1[c]	>1
Romania	n.d.	>1[c]	>1
Ukraine	n.d.	>2[c]	>2
Poland	0.3- 0.4[b]	1.2[b]	1.5
Austria	~0[d]	0.6–0.8[d]	0.6–0.8

[a] IP 9.
[b] IP 7.
[c] IP 1.
[d] IP 13.
[e] IP 14.

In 2013, 0.6–0.8 million bundles were gained, of which '99%' were exported (IP 13). Importing countries have been the Netherlands, Germany and the UK (Fig. 2g), small amounts also go to Italy and Belgium (Führer, 2010). The tremendous export drop in the middle of the 1990s (Fig. 2g) is to explain by four enterprises giving up reed cutting in 1994/1995 (IP 13).

3.4.8. Other exporting countries (alphabetical order)

Estonia is producing 0.8–1.5 million bundles per year (Lautkankare, 2007), harvested by ten companies (Miljan, 2013). Rough estimations based on the annually thatched roof area of 15,000–20,000 m^2 (Lautkankare, 2007) suggest that the domestic consumption is 0.18–0.24 million bundles. Thatched buildings are especially typical for Western Estonia and the islands Hiiumaa, Muhu and Saaremaa (Lilleste and Kams, 2013). Reed exports go mainly to Denmark, Sweden, Germany, the Netherlands and the USA (Lautkankare, 2007).

Reed roofing in *Latvia* was mentioned by Miljan (2013). High quality thatching reed is harvested from Pape Lake of which the majority is exported to Central and Western Europe (Laizans, 2013), thus Latvia is presumably a net exporter. No information could be gathered about the production volume, but the total reed area in lakes is 13,200 ha, equivalent to 97,000 tons of winter reed (Čubars, 2012).

Lithuania has a reed bed area of 4,995 ha (Iital et al., 2012). No other information could be gathered about reed used in thatching, but similar conditions as in Estonia and Latvia can be anticipated.

3.4.9. Summary exporting countries

Table 6 provides an overview about the main reed exporting countries, their domestic consumption and export volumes. This study classified countries as 'exporting countries', when production exceeds the domestic consumption. The limited amount of domestic reed produced in 'importing countries', is generally utilised locally and not exported.

Table 5
Total indigenous thatching reed production at Lake Neusiedl in Austria from 1960 to 2013.

		1960s	1970s–1980s	End of 1980s	1990s–2010	2010	2013
Indigenous reed	Million bundles	>2.78[a]	1.39–2.78[a]	0.63-0.89[a]	<1.67[a]	1[a]	0.6–0.8[b]

Bundles were converted from the locally common meter bundles to standard bundles using a factor of 2.78 that was calculated via the circular area (1 m/0.6 m circumference → 796 cm^2/286 cm^2).
[a] (Führer, 2010).
[b] IP 13.

Table 7
Total consumption in Europe based on (a) survey data and (b) summed up estimates for single countries (the Netherlands, Germany, UK, Denmark, Ireland, Hungary, Poland, and Estonia).

Period	1990–1998	1999–2007	2008–2012	2013	Outlook (2025)
Total consumption	Million bundles				
(a) Estimates for Europe	6[a]–10[b]	10[b]–20[c]	10[b]–12[c]	7[d]–15[c]	15[c]
(b) Summed up estimates for single countries	17.5	12–19.8	10.5–17.5	8.3–13.2	17.5–19

[a] IP 13.
[b] IP 12.
[c] IP 6.
[d] IP 7.

3.5. Neutral countries

This category includes countries known for a reed using culture, but a lack of data on domestic consumption, export or import hampered a classification as net importers or net exporters. In the *Czech Republic* reed is used as building material (Lautkankare, 2007), but no other information could be gained. *France* has regionally a domestic reed thatching culture and 1,500 ha of Mediterranean reed beds are used for cutting thatching reed for exports to Northern Europe (Poulin and Gaétan, 2002). *Italy* is known as a destination for reed from Lake Neusiedl (Führer, 2010) and the EU statistic confirms imports from e.g. China, Hungary, Turkey, Austria (all data not shown), and Romania for whose exports Italy ranks third (Fig. 2b). *Norway* seems to have a limited reed thatching culture (Lautkankare, 2007). *Sweden* has vast reed beds with more than 230,000 ha (Iital et al., 2012) and a long tradition in straw and reed thatching, although the latter dominates 90% of all thatched roofs today (International Thatching Society, 2015). After the fall of the Iron Curtain, cheaper reed became available which caused an increase in thatched roofs in South Sweden (ibid.). The current total consumption is estimated with 0.6 million bundles (IP 7).

3.6. Total Europe

Europe is the largest market for thatching reed worldwide. The *total consumption* of at least 7 million bundles equals 29,400 tons of reed (assuming an average weight of 4.2 kg/bundle). The market saw a general increase since 1990 (Table 7), growing strongly in the Netherlands and slightly in Germany (IP 6; IP 14) as well as in Denmark and the UK (Table 4). The consumption dropped sharply after 2007 (Table 7), when the financial crisis caused a temporary decline especially in the Netherlands and France. In 2013, the market had not totally recovered, but will probably in the long run. Currently, the demand for thatching reed is pushed by low interest rates, which encourage homeowners to invest in their properties.

Table 7 compares (a) responses from single interviewees about the total European consumption with (b) summed up data obtained for single European countries. The numbers of (a) are in the middle of the wide range of (b) that include survey and literature data. Generally, the values from literature are smaller than those obtained from interviews. The table shows also the weak points of separating data into time periods, which cannot reflect rapid changes properly. Whereas the statistical data on exports presented in Fig. 2 are compiled annually and therefore reflect changing importance of mass flows well, we detected a discrepancy between the export of a country into a specific country (e.g. Ukraine to Germany) and import statistics of this country (Germany from Ukraine). Export and import statistics should be equal. An explanation could be a different application of European CN-codes or imprecise statistics of the member states.

Over the past decades, a general change in the *import pattern* could be seen. In the beginning of the 20th century most of the thatching reed in Western Europe was produced locally. With wetland loss due to drainage, increasing environmental regulations and rising production costs, more and more reed was imported from Eastern Europe. This development accelerated after the fall of the Iron Curtain. In recent years, however, countries in Eastern Europe started to catch up economically with Western Europe, bringing up a higher awareness for environmental protection and similar restrictions for reed bed harvesting. Consequently, China with its vast reed areas has become an important single supplier and the trend will continue most likely.

The *reed price* varies from year to year and depends on many different factors, such as weather, living and labour costs, transportation distance, quality, bundle size, origin, etc. The purchasing country plays a role, too, as for example higher end consumer prices can be obtained in the Netherlands than in Germany (IP 14). In general, a normal price per bundle is 2.00–3.00 € (see also Table 3; Table 4). The obtained data are too weak to come to a final conclusion on the price development since 1990, but prices seem to be more or less stable, when inflation is taken into account (IP 1). *Thatching costs*[1] (material and labour) are about 38 € m^{-2} in Estonia (Nordling, 2008), 54–93 € m^{-2} in UK (Haslam, 2009), 70–90 € m^{-2} in the Netherlands, 80–90 € m^{-2} in Finland (IP 6; Lautkankare, 2007; Rauvola, 2007), 75–103 € m^{-2} in Germany (Schrader, 1998), and 186 € m^{-2} in Ireland (Mullane and Oram, 2005).

Additional sources of information on demand and consumption are the total number of thatched roofs and the area (m^2) thatched per year (Table 8). In the UK a declining number of thatched houses can be seen for the time between 1800 and 1960, further continuing until 2013. The Netherlands saw a sharp increase in newly thatched houses between 1999 and 2008.

During the last three decades, an *early decay* of reed thatched roofs has been observed which degraded confidence in reed as a roofing material and the whole reed thatching industry (Anthony, 1999; Gessner, 2001; Haslam, 1989; Kirby and Rayner, 1989; Wykes, 2010). The reasons are still not totally explored but seem to be a combination of several factors as improper construction, bad quality of reed, wetter climate in Europe and more aggressive fungi (Anthony, 1999; Wykes, 2010). Chinese reed seems not to be effected so far (Wykes, 2010). Hence, it was highlighted by many responders that a good quality control and international standards are necessary to ensure the reed business on long-term. Since a shortage of reed leads to the occurrence and sale of bad quality reed on the market (IP 6), an increased supply of high quality reed may also reduce the problem with rapid decay.

However, all kind of stakeholders involved in the reed business express strong concern that the *domestic supply* will further decline and the dependence on imports, in particular from China, will increase. At the same time, many interviewees disagree with the far distant importation. On the one hand they have environmental concerns because of emissions from transportation and missing consideration of wildlife interests and on the other hand they see thatching as a cultural and traditional craft which should use

[1] All values converted to € and inflation adjusted (www.fxtop.com) to October 1st, 2013.

Table 8
Thatched roofs per country and estimated demand of bundles per year assuming a consumption of 12 bundles per m^2 roof.

Country	Total number of thatched roofs	Newly and renewed thatched area per year	Converted into bundles per year
		m^2	Million bundles
UK	1,000,000 (1800), 35,000 (1960), 24,000 (2005)[a]	n.d.	n.d.
Germany	30,000-100,000 (2004)[b,c]	250,000 (n.d.)[c]	3[c]
Denmark	42,000 (2004)[f]	n.d.	n.d.
Netherlands	150,000 (2008)[d]	600,000 (1992)[e], 350,000 (1999)[d], 800,000 (2008)[d]	7.2 4[d] 8.7[d]
Estonia	n.d.	15,000–20,000 (n.d.)[f]	0.18–0.24

[a] (Thatch.org, 2005).
[b] (Asendorpf, 2007).
[c] (QSR, 2008).
[d] (Horlings, 2012).
[e] (Fraanje, 1997).
[f] (Lautkankare, 2007).

local resources. Even if many interviewees raised concerns about decreasing indigenous supply it was not necessarily due to loss of wetlands as it was until the 1990s. In contrast, many wetlands have been restored, but strict environmental regulations, high nutrient loads or difficult harvesting conditions hinder the exploitation on many sites. A promising option is to cultivate reed on rewetted peatlands that were formerly drained for conventional agriculture (Schäfer, 1999; Wichtmann, 1999). The rewetting of large areas reduces the conflicts with nature conservation aims, typical for small reed beds, and allows the operation of efficient large-scale harvesting machinery thus reducing the production costs. Since the drainage of peatlands causes subsidence, soil degradation as well as high greenhouse gas and nutrient emissions the shift from dry arable land or grassland to wet reed beds would allow a sustainable land use with many synergies for climate, water quality, and biodiversity (Wichtmann et al., 2010). This approach of wet peatland use, called paludiculture, has been widely recommended recently, e.g. by the FAO (Biancalani and Avagyan, 2014).

4. Conclusion

Reed used in thatching has a long tradition in Europe and became more popular again in recent years. Thatched houses are common along the Baltic and North Sea and form an essential part of cultural landscape in many regions. During the last 25 years, the Netherlands has been consuming annually 5–10 million reed bundles. Other important countries are Germany, Denmark and the UK with a consumption of around 2–3 million bundles each. All of them are unable to meet their demand from domestic resources and rely on the import of thatching reed up to a rate of 70–85% of the total consumption. Thus, thatching reed developed from the locally available, cheap roofing material in former times to a globally traded market product nowadays.

Obviously, the reed production decreased in Western Europe during the second half of the 20th century and was replaced by imports from Eastern Europe. EU data on trade statistics for the time from 1990 showed the different relevance of single countries with for instance Hungary and Ukraine exporting mainly to the Netherlands and Germany, Romania to Germany and Poland to Denmark as well as changes over time. Since the beginning of the 21th century, the production in Eastern Europe declined, too, due to similar reasons as in Western Europe before. At the same time local initiatives tried to increase the indigenous reed production and more potential reed became available through wetland restoration campaigns in Western Europe. In the meantime, the lack of European reed has been replaced by imports from China, -especially to the Netherlands since 2005/2006.

In conclusion, we can expect that the consumption will remain on a high, but roughly stable level, for the next years. China, which has vast reed resources available, will remain one of the main suppliers and possibly even increase its export volume. However, there is a chance that indigenous reed in Western Europe can play a more important role again, but it has to overcome many challenges, such as compensating high labour costs by efficient harvesting machinery and reducing conflicts with nature conservation restrictions by increasing the overall wetland area, e.g. through restoration and rewetting agriculturally used peatlands (paludiculture). Finally, reed as a construction material relies on a good image; fast spreading rumours originating from single examples of early decaying reed roofs can endanger the market developments. Promotion by an international thatching society, quality certificates for the reed and construction standards are means to ensure the long-term success.

Acknowledgments

We thank all interviewees for their cooperation making this study possible as well as Wendelin Wichtmann, Henk Horlings and Tom Hiss for valuable comments on a first draft of the manuscript.

References

Alsbury, S., 2010. Stodmarsh sustainable reed cutting—feasibility study. Natural England. RSPB, Wareham, UK, pp. 45.
Anthony, P.I.A.A., 1999. The macrofungi and decay of roofs thatched with water reed, *Phragmites australis*. Mycol. Res. 103, 1346–1352.
Asendorpf, D., 2007. Oben modert's. DIE ZEIT. http://www.zeit.de/2007/32/T-Reetdach (accessed 20.03.15).
Bateman, S., Turner, R.K., Bateman, I.J., 1991. Socio-economic impact of changes in the quality of thatching reed on the future of the reed growing and thatching industries and on the wider rural economy. Rural Development Commission London, pp. 94.
Biancalani, R., Avagyan, A. (Eds.), 2014. Towards climate-responsible peatlands management. Mitigation of Climate Change in Agriculture Series 9. FAO, Rome, pp. 117.
Boar, R.R., Kirby, J.J.H., Leeming, D., 1999. Variations in the quality of the thatching reed *Phragmites australis* from wetlands in East Anglia, England. In: Marriott, S.B., Alexander, J. (Eds.), Floodplains. Interdisciplinary Approaches. Geological Society, London, 145–151.
BRGA (British Reed Grower's Association), no date. Buying and selling reed. A description of reed qualities. pp. 6. http://www.brga.org.uk/files/Download/BuyingandSellingReed.pdf (accessed 20.03.15).
Broads Authority, 2012. Action plan for the reed and sedge cutting industry. Norfolk. pp. 9.
Cox, J., Letts, J., 2000. Thatch. Thatching in England 1940–1994. English Heritage Research Transactions, vol. 6. James & James (Science publishers), London, pp. 101.
Čubars E., 2012. Analysis of reed-covered surface and of potential biomass in Latvia's Lakes. pp. 2. http://www.cofreen.eu/index.php/en/project/publications/57-analysis-of-reed-covered-surface-and-of-potential-biomass-in-latvias-lakes (accessed 20.03.15).
Dadaser-Celik, F., Coggins, J.S., Brezonik, P.L., Stefan, H.G., 2009. The projected costs and benefits of water diversion from and to the Sultan Marshes (Turkey). Ecol. Econ. 68, 1496–1506.
DeLaCruz, A., 1978. The production of pulp from marsh grass. Econ. Bot. 32, 46–50.
Dickie I., 2001. The economics of reedbed management in the UK. RSPB Sandy. pp. 15. http://www.brga.org.uk/files/cgi-bin/EconomicsofReedbedManagementintheUK.pdf (accessed 20.03.15).
EC (European Commission), 1995. Wise use and conservation of wetlands. Communication from the Commission to the Council and the European Parliament. COM (95) 189 final, 29 May 1995, pp. 62.
EC (European Commission), 2011. Explanatory notes to the Combined Nomenclature of the European Union. Off. J. Eur. Union 2011/C 137, pp. 404.
ELP (Ecology Land and People), Ash, N., 2010. New opportunities for the sustainable management of fens: Reed pelleting, composting and the productive use of fen harvests. Broads Authority. pp. 66.
English Heritage, 2000. Thatch and thatching: a guidance note. UK: London. pp. 19.
Fraanje, P.J., 1997. Cascading of renewable resources hemp and reed. Ind. Crops Prod. 6, 201–212.
Führer, E., 2010. Schnittpunkte der Schilfwirtschaft und des Naturschutzes am Neusiedler See (Intersections of reed economy and nature conservation at Lake Neusiedl). Diploma thesis, BOKU – Universität für Bodenkultur (University of Natural Resources and Life Sciences), Vienna, pp. 228.

George, M., 1992. The Land Use, Ecology and Conversation of Broadland. Packard Publishing, Chichester, UK, pp. 558.
Gessner, M.O., 2001. Mass loss, fungal colonisation and nutrient dynamics of *Phragmites australis* leaves during senescence and early aerial decay. Aquat. Bot. 69, 325–339.
Hanganu, J., Dubyna, D., Zhmud, E., Grigoras, I., Menke, U., Drost, H., Stefan, N., Sarbu, I., 2002. Vegetation of the biosphere reserve 'Danube Delta' - with transboundary vegetation map. Danube Delta National Institute, Romania; M.G. Kholodny—Institute of Botany & Danube Delta Biosphere Reserve, Ukraine and RIZA, The Netherlands. RIZA Rapport 2002.049 Lelystad, pp. 90. Haslam, S.M., 1989. Early decay of *Phragmites* thatch: an outline of the problem. Aquat. Bot. 35, 129–132.
Haslam, S.M., 2009. The reed. First published 1969 by Norfolk Reed Growers Association, Norwich. Updated edition by the British Reed Growers Association, Norwich. pp. 38.
Haslam, S.M., 2010. A book of reed (*Phragmites australis* (Cav.) Trin. ex Steudel, formerly *Phragmites communis* Trin.). Forrest Text. pp. 254.
Hawke, C.J., Jose, P.V., 1996. Reedbed management for commercial and wildlife interests. RSPB, pp. 212.
Horlings, H., 2012. Die (rieten) dakenmarkt in Nederland. (The (thatched) roof market in the Netherlands), unpublished, pp. 2.
Iital, A., Klõga, M., Kask, Ü., Voronova, V., Cahill, B., 2012. Reed harvesting, in: Schultz-Zehden, A., Matczak, M. (Eds.), Submariner Compendium. An Assessment of Innovative and Sustsainable Uses of Baltic Marine Resources. pp. 103–124.
Ikonen, I., 2008. Introduction. In: Stenman, H. (Ed.), Reed Construction on the Baltic Sea Region. Turku University of Applied Sciences, Turku, pp. 10–13.
Ikonen, I., Hagelberg, E., (Eds.), 2007. Read up on reed! Turku, Finland. pp. 124.
International Thatching Society, 2015. Thatchers and thatching in Sweden. http://thatchers.eu/content/sweden (accessed 20.03.15).
Kask, Ü. (Ed.), 2013. COFREEN Project – Reed for Bioenergy and Construction. Tallinn University of Technology, pp. 107.
Kent Wildlife Trust, 2005. Reedbeds. Kent Habitat Action Plan. Plan Number 22. pp. 4.
Kirby, J.J.H., Rayner, A.D.M., 1989. The deterioration of thatched roofs. Int. Biodeterior. 25, 21–26.
Kitzler, H., Pfeifer, C., Hofbauer, H., 2012. Combustion of reeds in a 3 MW district heating plant. Int. J. Environ. Sci. Dev. 3, 407–411.
Knoll, 1986. Der Schilfschnitt am Neusiedler See (Reed harvest at Lake Neusiedl), in: Geographisches Jahrbuch Burgenland. pp. 34-67.
Köbbing, J.F., Thevs, N., Zerbe, S., 2013. The utilisation of reed (*Phragmites australis*)—a review. Mires Peat 13, 1–14.
Komulainen, M., Simi, P., Hagelberg, E., Ikonen, I., Lyytinen, S., 2008. Reed Energy-Possibilities of Using the Common Reed for Energy Generation in Southern Finland. Turku University of Applied Sciences reports 67, Turku, pp. 81.
Laizans, A., 2013. Business models and social-economic effects of reed business. In: Kask Ü (Ed.), Guidebook of Reed Business. Tallinn University of Technolgy, pp. 99–107.
Lautkankare, R., 2007. Reed construction in the Baltic Sea region. In: Ikonen, I., Hagelberg, E. (Eds.), Read up on Reed. Southwest Finland Regional Environment Centre, Turku, pp. 73–80.
Lautkankare, R., 2008. Reed as a building material. In: Stenman, H. (Ed.), Reed Construction in the Baltic Sea Region. Turku University of Applied Sciences Reports 68, Turku, pp. 89–101.
Lilleste, K., Kams, M., 2013. Thatched roof as an insulation layer. In: Kask, Ü. (Ed.), Guidebook of Reed Business. Tallinn University of Technology, pp. 50–55.
Miljan, J., 2013. Reed harvesting for construction purposes, reed's quality and harvesting technolgy. In: Kask, Ü. (Ed.), Guidebook of Reed Business. Tallinn University of Technolgy, pp. 21–25.
Millennium Ecosystem Assessment, 2005. Ecosystems and human well-being: Wetlands and water. Washington, DC. pp. 80.
Moir, J., Letts, J., 1999. Thatch. Thatching in England 1790–1940. English Heritage Research Transactions, vol. 5. James & James (Science publishers), London, pp. 218.
Mullane, F., Oram, D., 2005. Report on the present and future protection of thatched structures in Ireland. Volume 2: Supporting Information. pp. 27.
Myllyniemi, J., Virtanen, M., 2013. Common Reed. In: Kask, Ü. (Ed.), Guidebook of Reed Business. Tallinn University of Technology, pp. 9–15.
National Academy of Sciences, 1976. Making Aquatic Weeds Useful: Some Perspectives for Developing Countries. National Academy of Science, Washington, D.C. pp. 175.
Nordling, A., 2008. Reed roofs in Áland. In: Stenman, H. (Ed.), Reed Construction on the Baltic Sea Region. Turku University of Applied Sciences, Turku, pp. 39–45.
Painter, M., Smith, K., Gilbert, G., 1995. An Inventory of British Reedbeds 1993, Conservation Science Report. Royal Society for the Protection of Birds, Sandy.
Pitkänen, T., 2006. Missä ruokoa kasvaa? –Järviruokoalueiden satelliittikartoitus Etelä-Suomen ja Viron Väinämeren rannikoilla. Turun ammattikorkeakoulun puheenvuoroja 29, Turku, pp. 85.
Poulin, B., Gaétan, L., 2002. Effect of winter cutting on the passerine breeding assemblage in French Mediterranean reedbeds. Biodivers. Conserv. 11, 1567–1581.
Prosman, A., 2015a. Ungarn Reet (Hungary reed). http://www.prosman.de/d-ungarn.htm (accessed 2015-03-20).
Prosman, A., 2015b. China Reet (China reed). http://www.prosman.com/lagerchina.htm (accessed 20.03.15).
QSR (Gesellschaft zur Qualitätssicherung Reet mbH), 2008. Reet als Dacheindeckungsmaterial. Qualitätssicherung und -Erhaltung eines Baustoffs aus nachwachsenden Rohstoffen (Reed as roofing material. Quality assurance and maintenance for a renewable construction material). Project 25,018–25; DBU. pp. 182.
Rauvola, R., 2007. Launch and Marketing of Thatched Roofs in Nauvo. Turku University of Applied Science, pp. 93.
Ritterbusch, D., 2011. Nutzung von Rohr/Schilf- ein umweltverträgliches Entwicklungspotenzial für die Fischerei? (Utilisation of Reed–an Environmentally Friendly Potential for Development for the Fishery?), Schriften des Instituts für Binnenfischerei e.V. Potsdam–Sacrow; Band 30. Potsdam, pp. 78.
Rodewald-Rudescu, L., 1974. Das Schilfrohr (The reed). E. Schweizerbartsche Verlagsbuchhandlung, Stuttgart. 302 pp.
Rudescu, L., Niclescu, C., Chivu, I.A., 1965. Monografia Stufului din Delta Dunarii. (Monograph of Reed in the Danube Delta). Editura Academiei Republicii Socialiste Romania, Bucharest, pp. 542.
Rural Development Commission, 1988. The Thatcher's Craft. First published 1960. London pp. 22.
Schäfer, A., 1999. Schilfrohrkultur auf Niedermoor - Rentabilität des Anbaus und der Ernte von *Phragmites australis* (Reed cultivation on fens - Economic feasibility of growing and harvesting *Phragmites australis*). Arch. Nat. Conserv. Landsc. Res. 38, 193–216.
Schattke, W., 1992. Das Reetdach- Natürliches Wohnen unter sanftem Dach - Von der Uhrzeit Bis Heute (The thatched roof ?Natural Living Under Soft Roof—From Prehistoric Times Till Today), 3rd ed. Christians Verlag, Hamburg, pp. 263.
Schrader, M., 1998. Reet & Stroh als historisches Baumaterial. Ein Materialleitfaden und Ratgeber (Reed & Straw as Historic Construction Material. A guidebook). Anderweit Verlag GmbH, Suderburg-Hösseringen, pp. 195.
Schwarz, K.-U., Greef, J.-M., 2011. Anbau und Verwertung von Miscanthus als Material zur Dacheindeckung und für andere Nutzungen (Cultivation and processing of Miscanthus as roofing material and for other utilisations). pp. 48.
Silva, J.P., Phillips, L., Jones, W., Eldridge, J., O'Hara, E., 2007. LIFE and Europe's wetlands. Restoring a vital ecosystem. Luxembourg. doi:10.2779/22840 pp. 65.
Sluis, T. van der, Rii, O., Poppens, R., Lesschen, J.P., 2013. Reed resources in Poltava Oblast, Ukraine: biodiversity conservation and bioenergy production, in: Reed as a Renewable Resource, 14-16.02.2013, Greifswald, Germany.
Suna, E., 2008. Reed roofs in Finland. In: Stenman, H. (Ed.), Reed Construction on the Baltic Sea Region. Turku University of Applied Sciences, Turku, pp. 33–38.
Tanneberger, F., Tegetmeyer, C., Dylawerski, M., Flade, M., Joosten, H., 2009. Commercially cut reed as a new and sustainable habitat for the globally threatened Aquatic Warbler. Biodivers. Conserv. 18, 1475–1489, http://dx.doi.org/10.1007/s10531-008-9495-0.
Tarr, J.A., Rooyen, M.W., Bothma, J.D.P., 2004. The response of *Phragmites australis* to harvesting pressure in the Muzi swamp of the Tempe elephant park, South Africa. Land Degrad. Dev. 15, 487–497.
Terwan, P., van der Fluit, N., 2011. Verkenning van de rietsector in Nationaal Park Weerribben-Wieden (Exploring the reed sector in the National Park Weerribben-Wieden). Utrecht/ De Wijk. pp. 50.
Thatch.org, 2005. Thatch roof owners, Thatching Information, for anyone responsible for the upkeep or interest in thatched property. http://thatch.org/index.htm (accessed 20.03.15).
Thesinger, W., 2007. The Marsh Arabs. Penguin Classics, pp. 233, First published by Longmans, Green 1964.
Thevs, N., Zerbe, S., Gahlert, E., Mijit, M., Succow, M., 2007. Productivity of reed (*Phragmites australis* Trin. ex Steud.) in continental-arid NW China in relation to soilgroundwater, and land-use. J. Appl. Bot. Food Qual. Bot. 81, 62–68.
Van der Putten, W.H., 1997. Die-back of *Phragmites australis* in European wetlands: an overview of the European research programme on reed die-back and progression (1993–1994). Aquat. Bot. 59, 263–275.
White, G., 2009. The future of reedbed management. Information and Advice note Version 7, RSPB, pp. 11.
Wichmann, S., 2016. Micro-economic aspects of paludiculture, in: Wichtmann, W., Schröder, C., Joosten, H. (Eds.), Paludiculture - Wet peatland management for regional development, climate and biodiversity (in press). Schweizerbart, Stuttgart.
Wichtmann, W., 1999. Nutzung von Schilf (*Phragmites australis*) (The utilisation of reed). Arch. Nat. Conserv. Landsc. Res. 38, 217–231.
Wichtmann, W., Schäfer, A., 2007. Alternative management options for degraded fens - Utilisation of biomass from rewetted peatlands. In: Okruszko, T., Maltby, E., Szatylowicz, J., Swiatek, D., Kotowski, W. (Eds.), Wetlands: Monitoring, Modeling and Management. Taylor & Francis/Balkema, Leiden, The Nettherlands, pp. 273–279.
Wichtmann, W., Tanneberger, F., Wichmann, S., Joosten, H., 2010. Paludiculture is paludifuture: Climate, biodiversity and economic benefits from agriculture and forestry on rewetted peatland. Peatlands Int., 48–51.
Wykes, J.W., 2010. Premature decay on roofs thatched with water reed. Winston Churchill Memorial Trust. http://www.wcmt.org.uk/sites/default/files/migrated-reports/856_1pdf (accessed 20.03.15). pp. 55.
Yates, T., 2006. The use of non-food crops in the UK construction industry. J. Sci. Food Agric., 1790–1796, http://dx.doi.org/10.1002/jsfa.

Paper III

Becker, L., Wichmann, S. & Beckmann, V. (2020)

Common reed for thatching in Northern Germany:

Estimating the market potential of reed of regional origin.

Resources 9 (146): 1–21.

resources

MDPI

Article

Common Reed for Thatching in Northern Germany: Estimating the Market Potential of Reed of Regional Origin

Lea Becker, Sabine Wichmann and Volker Beckmann *

Faculty of Law and Economics & Institute of Botany and Landscape Ecology, University of Greifswald, Soldmannstr. 15, D-17489 Greifswald, Germany; leabecker@hotmail.de (L.B.); wichmann@uni-greifswald.de (S.W.)
* Correspondence: volker.beckmann@uni-greifswald.de; Tel.: +49-3834-420-4122

Received: 1 October 2020; Accepted: 12 December 2020; Published: 16 December 2020

check for updates

Abstract: Reed has a long tradition as locally available thatching material, but nowadays thatch is a globally traded commodity. Germany and other major importing countries such as the Netherlands, the United Kingdom, and Denmark rely on high import rates to meet the national consumption. This study aimed at providing a detailed picture of the thatching reed market in Northern Germany and at assessing the market potential for reed of regional origin. A written survey among all thatchers in Northern Germany was carried out in 2019, arriving at an effective sample of 47 out of 141 companies. The results revealed that for the responding companies the majority of the reed (59%) was used for rethatching roofs completely, 24% for newly constructed roofs, and 17% for roof repairs. Reed from Germany held a low share of 17% of the total consumption in 2018. Own reed harvesting was conducted by less than 9% of the responding companies and given up during the last decades by another 26%. The total market volume of reed for thatching in Northern Germany was estimated for 2018 with a 95% confidence interval at 3 ± 0.8 million bundles of reed with a monetary value at sales prices of €11.6 ± 2.8 million. Based on the end consumer demand, the supply gap for reed of regional or German origin was estimated at 523,000 ± 392,000 bundles of reed equaling a market value of €1.9 ± 1.4 million, indicating high uncertainties. Most of the responding thatchers (70%) did not promote reed of regional origin, mainly due to insufficient availability but also a lack in quality was reported. The cultivation of reed in paludiculture, i.e., as climate-smart land use alternative to drainage-based agriculture on peatlands, can increase the availability of thatching reed in Germany and simultaneously reduce GHG emissions.

Keywords: *Phragmites australis*; thatching companies; value chain; market analysis

1. Introduction

Common reed (*Phragmites australis*) is one of the most widespread plants in the world and populates wetlands of various kinds [1]. Since time immemorial, people made use of different parts of the plant as well as of the reedbed itself [2]. A wide range of historical uses up to services appreciated only recently is described by Haslam [2], Kiviat [3], and Köbbing et al. [4]. While reed is an important resource for the pulp and paper industry in China [5,6], in Europe it is appreciated as building material.

The utilization of the long and thin reed culms as roofing material, i.e., for thatching, is one of the best known and most common applications in many European countries. In Germany, evidence for the use of reed for thatching comes from as early as 4000 BC, when the first Neolithic farmers settled at the coastline of the North and Baltic Sea [7]. Until today, thatched houses are commonly found in the coastal regions of Northern Germany and in regions with many inland lakes where they have a landscape-defining character. The thatcher's craft is included in the German Inventory of Intangible Cultural Heritage [8]. Thatched houses are valued for providing a pleasant living climate, for the renewable building material, and for its high aesthetic value [8,9]. An average estimate for the durability of a reed thatched roof is 40–50 years with possibly much longer lifetime for the Eastern or Northern side of the roof and very steep roofs [7]. Single cases of considerably shorter lifetimes are known as early or premature decay and have been described for reed thatched houses at least since the 1970s [10] but were increasingly observed in Germany at the turn to the 21st century [11]. The lifetime of a roof is influenced by many factors starting from the quality of the reed, over the construction of the roof up to the maintenance of the thatched roof. Repair work can be necessary from time to time as well as renewing parts especially exposed to wind and weather, like the roof ridge, which needs to be conducted normally every 15–20 years [12]. Every landscape has a traditional regional building and thatching culture with specific house types, roof shapes, or materials used for the roof ridge, e.g., variations of the Low German house, the Haubarg of the Eiderstedt peninsula, or log houses in the Spreewald [12]. Today, reed is not only used for rethatching historical monuments but also on newly build (holiday) houses and even for modern architecture, e.g., exploring the use of thatch for covering walls [13,14].

Despite its long tradition as locally available roofing material, reed for thatching is nowadays an internationally traded commodity. A first analysis of the European market identified major importing countries (the Netherlands, Germany, the United Kingdom, and Denmark) relying on imports of up to 85% of the national consumption [15]. One major reason of the low self-supply rate is the decline of reedbeds due to dyke construction, drainage, and cultivation of peatland and marsh land [12]. Additionally, the remaining reedbeds are defined as legally protected habitat by the Federal Nature Conservation Act in Germany and partly located in designated nature conservation areas. While the use of domestic resources has been increasingly restricted, reed was imported from East and Southeast Europe (e.g., Hungary, Romania) and since 2005 even from China [15]. The cultivation of reed as agricultural crop might improve the supply with domestic reed.

Common reed is considered as a promising paludicultural plant [16]. Paludiculture is defined as agriculture and forestry on wet or rewetted peatlands; it combines a productive use with the preservation of the peat body as long-term carbon store [17]. There is a high need to develop climate smart utilization options for rewetted peatlands. In Germany, drained peatlands encompass only 7% of the agricultural area but emit 37% of the national greenhouse gas emissions of agriculture and agricultural land use; in the EU 3% of the area are responsible for 25% of the emissions [18]. Being an emergent wetland plant, reed grows well at water levels near surface, which are needed to ensure peat preservation. In addition to reducing a large source of soil born GHG emissions, below-ground biomass may form new peat thus acting as sink for carbon captured from the atmosphere. Comparing three utilization options for reed, the harvest for thatching was the most profitable option compared to combustion and biogas generation [19]. When it comes to economic viability, the market potential of domestic reed plays an important role.

The research aimed at determining the market volume and market potential of reed of regional origin for thatching in Northern Germany. Specifically, it aimed to answer the following three research questions:

1. What is the current market volume of reed for thatching in Northern Germany?
2. What are the market shares of thatching reed from different origins?
3. What factors influence the demand and supply of reed of regional origin and how can its market potential be assessed?

In answering these questions, we add to the very sparse literature on reed markets and provide the first in-depth study on the market of thatching reed not only in Northern Germany but worldwide. The total quantity, the origin of reed, and quality attributes are investigated as key factors. The results are relevant beyond the scope of Northern Germany as similar situations, i.e., a high consumption of reed and a little self-supply rate, are found in other countries, in particular in the Netherlands, Denmark, and the United Kingdom. Furthermore, rewetting of peatlands and identifying economically viable utilization options is an issue worldwide in order to enhance nature-based climate solutions [20,21].

2. Materials and Methods

2.1. Study Site

Reed thatched houses are found mainly in the North of Germany, i.e., near the coasts, on the islands of the North Sea and the Baltic Sea, but also in areas rich of inland water like the "Spreewald" region south of Berlin [12]. In Southern Germany, the formerly rye straw thatched houses in the Black Forest are also thatched with reed that is nowadays more easily available than long straw [12]. We focused our study on Northern Germany since reed roofed houses are most common in this region. Only few thatched houses are present in the remaining parts of Germany, although straw thatch was a widespread roofing material of rural areas until the beginning of the 20th century [12]. The study region consists of the federal sates of Mecklenburg-Western Pomerania, Lower Saxony, Schleswig-Holstein, Brandenburg, Hamburg, and Bremen, the last two being city states (Figure 1).

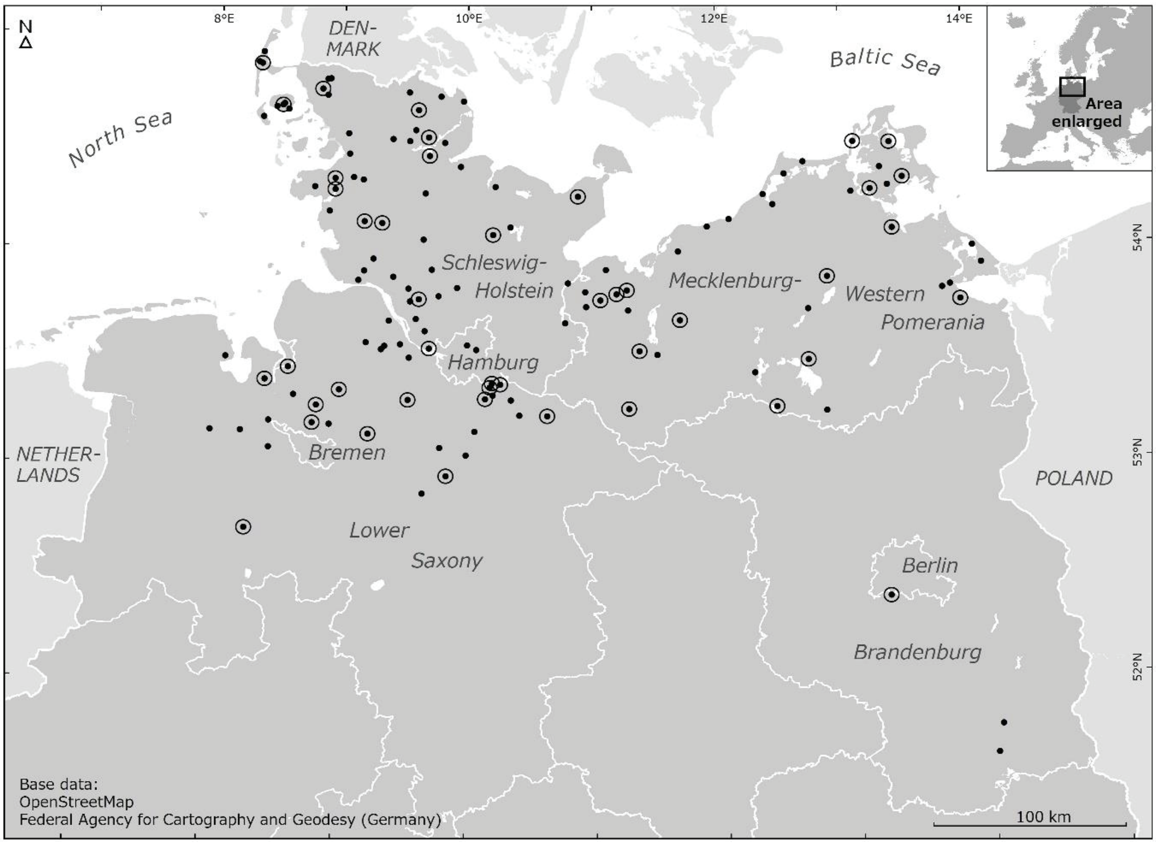

Figure 1. Northern federal states of Germany and the location of sampled (**all dots**) and responding (**large dots**) thatching companies.

2.2. Market Analysis

The analysis of the market of reed for thatching and the market potential of regional reed builds upon the concept of value chains [22,23] and product differentiation by country or regions of origins [24]. Figure 2 depicts the value chain and the main actors along the chain. The material flow goes from left to right, and the value grows accordingly with every step in the chain; the money-flow goes from right to left. Reed grows either in natural reed beds or is cultivated for being harvested. Cultivation may range from some management decisions taken by the landowner or the land user for existing reed beds (e.g., water management) up to the establishment of new reed beds by planting. In Germany, public authorities decide if, when, and how reed harvest can take place. Reed cutters harvest dry winter reed using simple or advanced technologies. Reed is tied and stored for further drying up. It is cleaned and retied to standardized bundles ready for thatching. A reed bundle, also referred to as a Euro bundle has a circumference of 60 cm [25]. The final demand for thatched houses generates the demand for thatching, the partial demand for trading, the partial demand for cleaning and retying, the partial demand for harvesting, and the partial demand for commercially used reed beds.

Figure 2. Value chain for reed as thatching material and value chain actors.

In this study, we focused on thatching companies being the key actors in the value chain by linking the final demand with the market for raw materials. Addressing thatching companies allowed us to estimate the total market volume for thatching reed (either in physical units of reed bundles or in monetary volume), the origin of reed used, as well as the market share distribution according to origins and among companies. Concerning the market of thatching services, we distinguished three different market segments: thatching new buildings, renewing roofs on old buildings, and repair work on thatched roofs. Thatchers are also able to assess different demands of the final consumer and create a demand for reed of different quality and origins by promotion and price policies. Similar to research that has been conducted for food, e.g., [26], we investigated the importance of reed of regional origin concerning e.g., current market share, demand from end consumer side, valuation of thatcher's side, availability, and market potential.

2.3. *Survey of Thatching Companies*

Surveys are well established instruments in market research in particular for gaining information on size and structure of markets and on the use of and attitudes to products [27]. The target population of this study were thatchers in Northern Germany. After extensive internet and business research a total number of 151 companies were identified. The whole identifiable population was sampled with a combined mail and internet questionnaire using the web-based software tool "EvaSys". To optimize data collection and quality assurance, the questionnaire was subjected to two rounds of pretests [28]. The survey was conducted in August 2019. The questionnaire and a cover letter with additional information were sent to 151 companies requesting participation either in a postal way (a stamped, self-addressed envelope was included) or in an online questionnaire via "EvaSys". One week after initial survey invitation, reminding took place via email or phone.

Because the questionnaire was sent to the entire identifiable population, a census approach was used. Ten businesses no longer existed, were not thatching any more, or were pure trading companies. These businesses were excluded. The population (N) finally included 141 thatching companies. Over the entire three-week response period (30 July–16 August 2019), 47 questionnaires were completed and returned. The response rate was thus 33%. The response rate for the individual federal states was between 24 and 100% (Table 1).

Table 1. Total number of sampled companies and response rates in the survey of thatchers in the federal states of Northern Germany carried out in 2019.

Federal State	Total Number of Companies	Response Rate		
		Number	Row Percent	Sample Percent
Schleswig-Holstein	58	14	24.1	29.8
Lower Saxony	37	13	35.1	27.7
Mecklenburg-Western Pomerania	39	16	41.0	34.0
Hamburg	4	2	50.0	4.3
Brandenburg	2	1	50.0	2.1
Bremen	1	1	100.0	2.1
Sum	141	47	33.3	100.0

2.4. Nonresponses, Representativity and Data Integrity

Not returned questionnaires, i.e., Unit-Nonresponses, are traditionally explained by "not-at-homes, "people unable to answer" (e.g., being actually ill), and "refusals" (e.g., cost of answering is higher than the expected benefit) [29,30]. For the present study, the first and second reason are unlikely due to the conduction of a written survey with a response period of several weeks. Some of the refusing thatchers provided their individual reason for not completing the survey like "no time", "not participating in surveys", "no interest", and "work only little with reed". We assume nonresponses to be random. No systematic bias could be observed, e.g., both very small and very large companies participated in the survey. Due to the lack of any information on the population of thatchers from other sources, the representativity of the sample cannot be assessed directly. Thus, by using the responses for extrapolating data to the total population we need to assume the effective sample being representative for thatchers in Northern Germany. The extrapolated data can partly be crosschecked with data from other sources.

Before conducting the data analysis, the data quality was checked. None of the questionnaires had to be discarded. A few obviously unrealistic values (outliers, inconsistency of values for dependent variables) were excluded from the analysis. Missing values occurred due to Item-Nonresponses or discarded answers. Listwise deletion, i.e., deleting complete cases due to missing values, was not an option due to the small sample size. Missing values were not replaced with substituted values (data imputation). Because all questionnaires were kept for analysis and no data imputation was conducted, the number of effectively sampled companies (n) differed depending on the analyzed question.

Unit- and Item-Nonresponses, even if occurring completely at random, always reduce the effective sample size and increase the sampling error and the variance of the estimates [31]. Taking this into account, we estimated the main extrapolated variables of interest at a confidence interval of 95%.

2.5. Data Analysis

2.5.1. Quantitative Analysis

For most variables basic descriptive statistics are reported, including mean (M), standard deviation (SD), sum, and sometimes min and max values. Histograms are presented only for the most important variables. For the purpose of extrapolation, we checked whether or not differences in the distribution of variables between companies located in different federal states exist. Only those federal states were compared in which the number of responses to the questionnaires was high enough to allow valid statistical statements to be made, i.e., Schleswig-Holstein, Lower Saxony, and Mecklenburg-Western Pomerania. Because the data were not normally distributed and differences between independent samples were to be investigated, the Kruskal–Wallis test was applied in each case [32]. In addition, the sale-price differences between imported reed and reed from Germany were to be checked for their statistical significance in companies that offer both types of reed. Because these data were not normally distributed either, a Wilcoxon matched pair signed rank-Test was used [32]. Furthermore, a Fisher-exact test was carried out to identify a possible correlation between the promotion and the quality assessment of reed of regional origin. A linear regression analysis (ordinary least squares—OLS) was performed to check the relationship between the number of orders for thatching and the number of bundles installed. The values of a dependent variable (in this case the number of bundles installed in 2018) are to be traced back to independent variables (here the different orders). The statistical analysis of the data was conducted with the Statistical Package for Social Sciences (SPSS, Armonk, NY, USA). In all calculations, the level of statistical significance was set to $p \leq 0.05$ [33].

We calculated sampling errors to estimate the extent of the variation that is due to investigating a sample but not the whole population. The 95% confidence intervals (*CI*) for the expected population means (μ) were determined by using the following formula:

$$CI(\mu) = M \pm z_{\alpha/2} \frac{SD}{\sqrt{n}} \sqrt{\frac{N-n}{N-1}}$$

where M indicates the sample mean, $z_{\alpha/2}$ the z-value for $\alpha = 5\%$, that is 1.96, SD the sample standard deviation, n the sample size, N the population, and $\sqrt{N-n/N-1}$ the finite population correction factor [34]. For further mathematical procedures, rules for expected value calculation and propagation of uncertainties were applied [35].

2.5.2. Qualitative Analysis

Two open questions were asked concerning the promotion and the availability of reed of regional origin leading to qualitative statements. Inductive coding is one of the forms of content analysis defined by [36]. Instead of being based on theoretical assumptions, the inductive procedure uses only the available material as a starting point for category formation. Inductive coding was suitable for the survey, since the lack of literature required an exploratory approach.

Because the quality of the results depends directly on the decisions of the rater, coding was accomplished independently by two raters and the coding was compared to check the quality of the category system. SPSS was used to calculate the measure for the randomly corrected agreement Cohens Kappa [33,36]. Cohens Kappa calculates the correspondence of the category assignment of text parts between the two raters and relativizes this by the probability of a random match [37]. The higher the agreement between the raters, the more independent are the results of the raters. In the calculation, the categorization of the answers to the question why reed of regional origin is not promoted resulted in a kappa of $\kappa = 0.951$ and the question why the demand for reed of regional origin cannot be met resulted in a kappa of $\kappa = 0.853$. Both kappas correspond to a very high match [38]. In the end, the two raters agreed upon a uniform category allocation for text parts that had been assigned to different categories, which formed the basis for the analysis of the frequencies in the results section.

2.6. Cross Validation

To validate the information of the survey, the results were compared with information about roofing standards and available trade data. The estimated number of bundles of reed used for thatching new and renewed roofs were compared with information on average roof sizes and average number of bundles used per square meter. The results of the stated origin of the bundles used by the thatchers was compared with the import figures on the EU portal "Eurostat" for 2018. For the latter purpose, the database "Eurostat" was called up [39]. Then, the database for international data (detailed data) was selected. The import of reed can be found in the EU trade to CN8 in 2018 under the products G14. Reed is classified under the trade code "1401 90 00". It is assumed that the other products covered by this code, e.g., raffia for plaiting, are of negligible importance [15]. The EU countries (EU28 INTRA), as well as Ukraine, Turkey, Belarus, and China were selected as partner countries and Germany as reporter for imports. The selection is based on the countries listed in the reed product data sheet [25]. As in the questionnaire, the comparative figures include Turkey, Belarus, and Ukraine as European imports.

3. Results

3.1. Thatching Companies

Most of the responding thatching companies are specialized on thatching. About two thirds of the companies (62%, n = 29) work with reed as the only roofing material, while 38% (n = 18) also use other materials. Some specialized thatchers are also trading reed (n = 2), harvesting reed (n = 4), or cultivating reed (n = 1). In terms of employment, all thatching companies can be classified as small and medium scale enterprises (SME) ranging from pure self-employment to a maximum of 28 full-time employees. On average, the companies employ almost six full-time employees (SD = 5.53). Part-time employment (n = 15) and seasonal employment (n = 4) are not very common. While 26% (n = 12) of the companies provided thatching services only in their local district, 11% (n = 5) covered all categories reaching from local district over other districts of their federal state to other federal states and even other countries. Services were provided for instance in the Netherlands, Belgium, Luxemburg, France, Great Britain, Ireland, Poland, Sweden, and Iran. In summary, the responding thatching companies in Northern Germany can be characterized as small and medium scale enterprises with a high level of specialization and a permanent labor force. The market orientation ranges between a very local market and a European market dominated by a regional and national market orientation.

3.2. Thatching Services and Market Development

The final market for thatching services can be divided into three market segments (1) thatching new roofs, (2) renewal of roofs, and (3) repair of roofs. Table 2 shows the number of orders carried out by responding thatchers in 2018. A total of 83 roofs were newly built and 231 roofs were completely renewed. There were also 1778 orders to repair a thatched roof. On average, one company carried out around 2 orders to cover newly built thatched roof houses, 6 orders for complete renovation, and 47 repairs. The SD indicates that there is a large variation for orders across companies, especially for repairs.

Table 2. Types of orders for thatching services of responding thatching companies in Northern Germany in 2018.

Type of Order	n	Number of Orders		
		Sum	Mean	SD
Newly constructed roofs	40	83	2.1	3.8
Completely renewed roofs	40	231	5.8	5.7
Repairs of roofs	38	1778	46.8	62.4

Thatchers were asked how they rate the development of the market for newly constructed roofs in the ten years before 2018 on a scale of 1–7, where 1 indicated greatly reduced and 7 greatly increased. Overall, the frequency of newly thatched houses in the past 10 years was assessed as slightly increasing (n = 41, M = 4.4, SD = 1.7). Thatchers were also asked how they assess the development of general roofing market relative to the thatching market on a Likert-Scale from 1—much worse to 7—much better. On average, the general market for roofing was considered to have developed slightly better (n = 46, M = 5, SD = 1.6).

3.3. Reed Bundles Per Company and for Thatching Services

The thatchers were asked how many Euro bundles of reed they installed in 2018. The distribution is depicted in Figure 3. Most of them installed less than 10,000 bundles with a minimum of 200 and a maximum of 80,000 bundles. For the sample of 35 respondents, a total of 750,575 bundles of reed were installed (M = 21,445, SD = 19,964).

In order to link the number of orders for thatching with the amount of reed, a linear regression through the origin was carried out (n = 30). The regression estimated that 2132 bundles ($p < 0.000$) were installed for each newly built house, 1923 bundles for each completely renewed roof ($p < 0.000$), and 24 bundles for each repair ($p = 0.521$). Overall, the number of orders significantly influenced how many bundles of reed were installed in 2018 ($F = 40.2$, $p < 0.000$). The regression explains 82% of the variance in the installed bundles. It should be noted that the repairs were not statistically significant, obviously, since the area size per order can vary greatly.

Thus, in terms of reed bundles used, the market for completely renewed roofs is estimated to be the largest (59% of the annually installed reed), followed by newly constructed roofs (24%), and finally roof repairs (17%), if the latter includes the residuals.

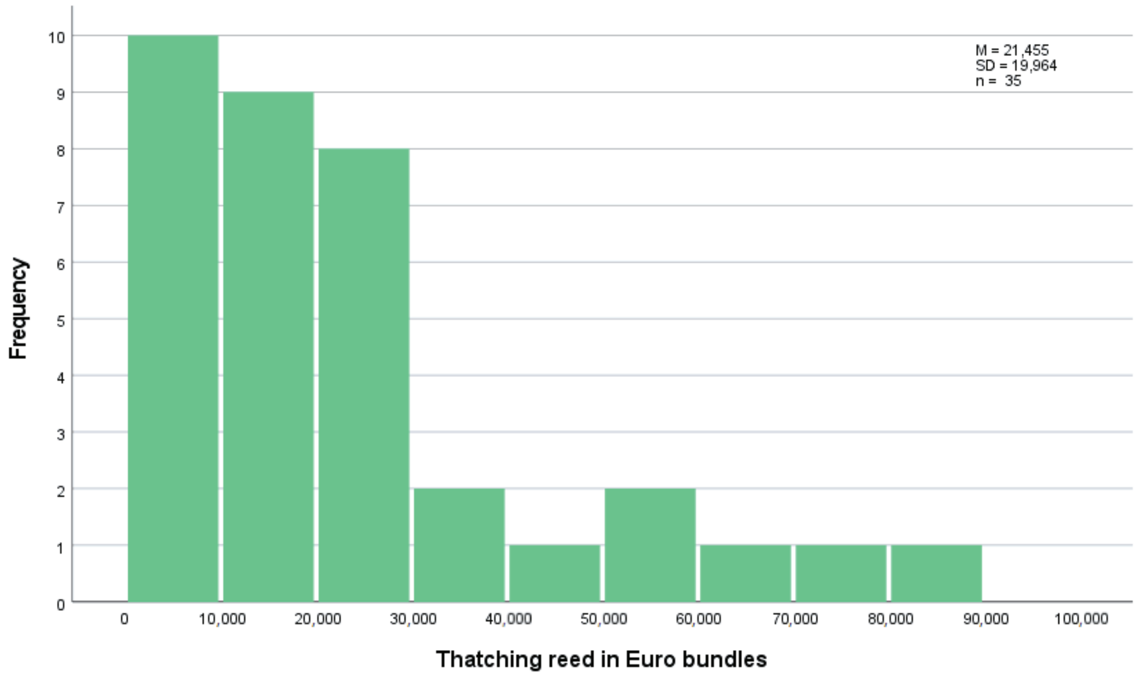

Figure 3. Quantity of Euro bundles of reed installed for thatched houses per responding thatching company in Northern Germany in 2018 (n = 35).

The results of the linear regression of the orders and installed bundles can be compared with the size of a roof and thus validated. The roof area of a single-family house in Germany is approximately 150 m^2 [40]. At least 12 bundles of thatch are required to cover one square meter of roof [7,41,42]. If the roof area is now calculated using the number of bundles installed per order, this amounts to an average of 178 m^2 for newly built houses and an average of 161 m^2 for renovated houses. Because these are realistic sizes, it can be assumed that the data given are consistent.

3.4. Market Shares by Origins of Thatching Reed

Thatchers were asked where the thatch came from in 2018. As can be seen in Table 3, the respondents indicated that 12.8% came from their respective federal state and a further 4.1% from other parts of Germany. A total of 4.3% came from the Polish part of Pomerania, i.e., the neighboring region of Mecklenburg-Western Pomerania, and the main part came from the remaining European market with 62.7%. In addition, 16.1% of the reed was imported from China.

Table 3. Origins of thatching reed used by responding thatching companies in Northern Germany in 2018 (n = 44).

Origins	Percentage of Reed	
	Mean	SD
The respective federal state	12.8	25.1
Other parts of Germany	4.1	13.9
Polish part of Pomerania	4.3	13.2
Other parts of the European market (including Ukraine and Turkey)	62.7	40.0
China	16.1	28.9

For validation, the information on the origin of reed for thatched roofs in Northern Germany can be compared with EU import statistics from 2018. Of the 6367 tons of reed imported to Germany, 80% came from the European domestic market (EU28 intra, Belarus, Turkey, and Ukraine) and 20% from China. The imports make up 100% of the reed used. For comparing these figures with the information from the questionnaire, the share of nonimported reed (17%) must be included. Considering an import rate of 83%, EU trade statistics reveal 66% of the reed coming from the European market and 17% from China. In comparison to the information provided by thatchers (67% from the European market, including the Polish part of Pomerania, and 16% from China), the percentage figures hardly differ.

3.5. Thatching Reed Sales Prices and Origins

Thatchers were asked for the price at which a Euro bundle is sold to the customer (Table 4). The thatchers stated that a Euro bundle of reed imported to Germany was sold to their customers for an average price of €3.90, while a Euro bundle of reed from Germany cost on average €3.57.

Table 4. Customer purchasing prices of thatching reed sold by responding thatching companies (in prices of 2018).

Origin	n	€/Euro Bundle			
		Mean	SD	Min	Max
Germany	25	3.57	0.87	2.5	5.5
Other countries	38	3.9	0.94	2.41	6.5

For companies selling reed from Germany as well as from other origins (n = 24), a Wilcoxon matched pair signed rank-Test indicated that thatching reed from Germany is offered at a significant slightly lower price ($p = 0.037$).

3.6. Purchasing Criteria of Thatchers

When purchasing reed, the origin of reed is a relevant criterion for 54% of the thatchers (Table 5). However, other criteria are more important. All thatchers stated that quality is an important purchasing criterion for them. Quality requirements for thatch according to the "Product data sheet for thatch" published by the "German roofing association" include: cleanliness, culm length, and breaking strength [25]. These criteria were considered as relevant by 91%, 87%, and 70% of the thatchers, respectively. In a question, where the thatchers should rank the three most important criteria, quality was the most important criterion for 56% and the second most important criterion for another 10% (n = 43). Origin was the most important criteria only for one thatcher (2%), and the second most important for three (7%).

Interestingly, price was a relevant criterion only for about one third of the responding thatchers. No thatcher mentioned price as the most important criterion; however, four thatchers mentioned price as the second and another three as the third most important criterion. Color of reed was least important.

Table 5. Criteria when purchasing reed for thatching of responding thatching companies in Northern Germany in descending order (n = 46).

Criteria	Frequency	Percent
Quality	46	100.0
Cleanliness	42	91.3
Culm length	40	87.0
Breaking strength	32	69.6
Culm wall thickness	26	56.5
Origin	25	54.3
Price	15	32.6
Storage and transportation	27	29.6
Color	9	19.6

3.7. Regional Origin of Thatching Reed and Quality

Regional origin is a fussy concept. Therefore, the thatchers were asked at first how do they understand the term "regional" in relation to reed. For the responding thatchers, "regional" primarily means reed from Germany (33%), from their own federal state (28%), and from their own district (26%) (n = 47). For only 5%, "regional" means from the entire European Single Market. As we had anticipated those diverse concepts of regionality, all further questions on regional reed applied a uniform definition: "Regional reed include all reed from a radius of up to 150 km".

Thatchers were asked how they assess the quality of regional reed as compared to other sources (Figure 4). On average the quality was assessed as equal. Of the respondents (n = 37), 10 thatchers considered the quality as superior and 14 as inferior. All thatching companies that were engaged in harvesting reed (n = 4) considered regional reed of superior quality.

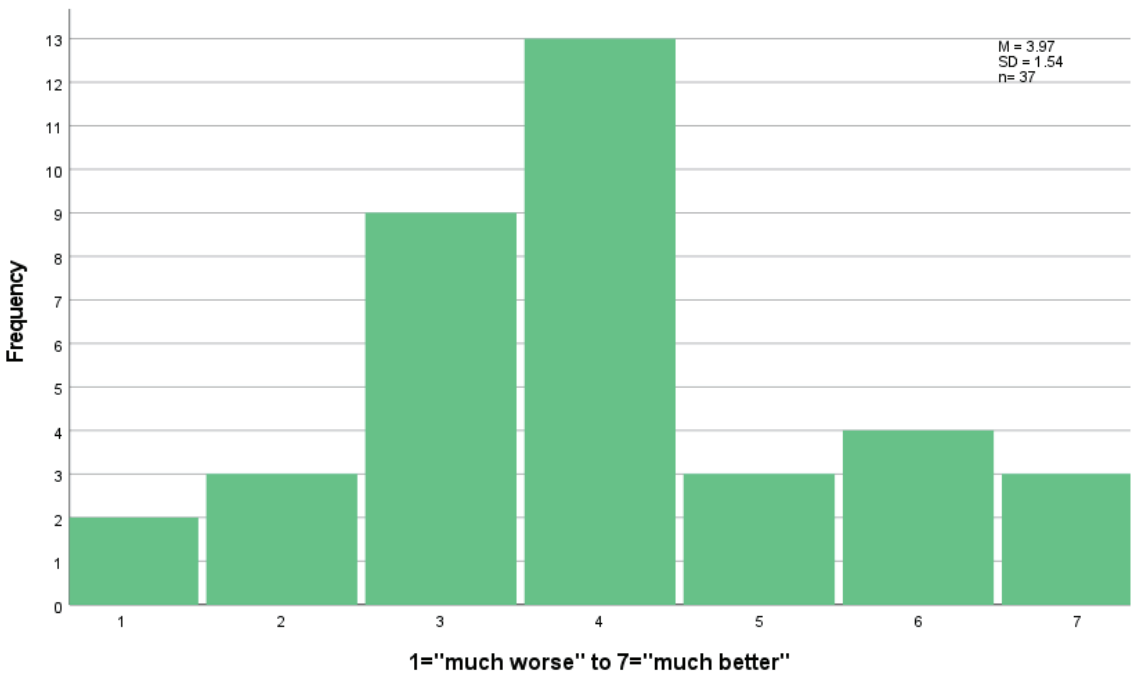

Figure 4. Quality assessment of regional reed as compared to other sources on a Likert-scale by responding thatching companies in Northern Germany (n = 37).

3.8. Demand for and Promotion of Reed of Regional Origin

Next to the importance thatching companies assigned to the origin of reed, we also asked for the demand on the part of building owners. The thatchers stated that on average 34% of their customers asked for reed of regional origin on their own (n = 45). Thatching companies with own reed harvest (n = 4) indicated a much higher demand shown by on average 75% of their customers. In the case of 29% of all thatching companies, no customer asked for thatching reed of regional origin (Figure 5).

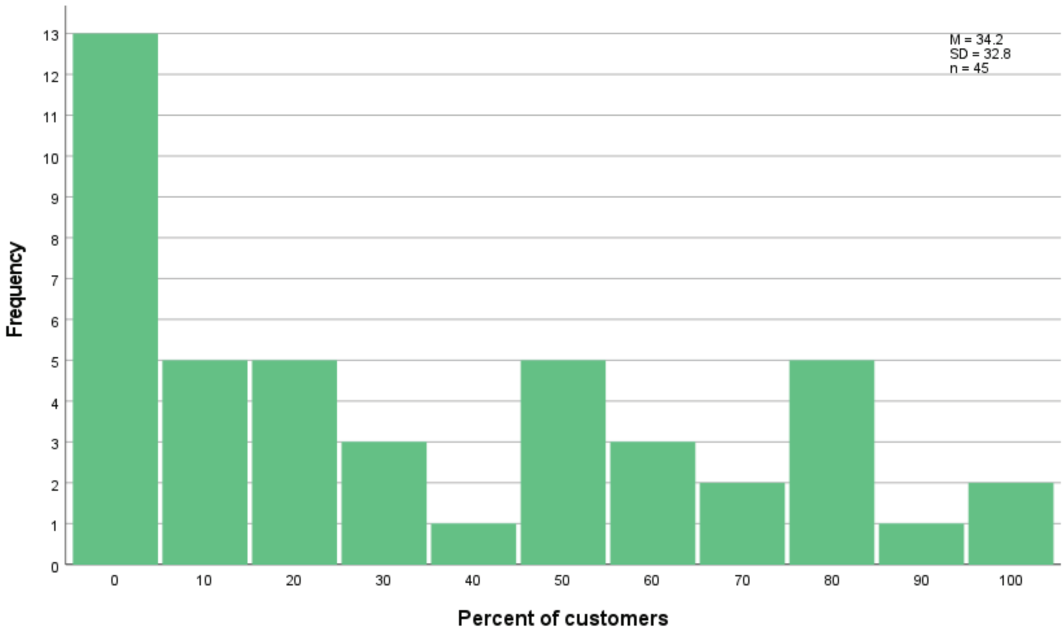

Figure 5. Percent of customers asking for thatching reed of regional origin on their own in responding thatching companies in Northern Germany (n = 45).

Assuming that the share of customers demanding regional reed approximates the share of demanded reed bundles, the before mentioned information can be used to calculate the market potential for reed of regional origin. For the sample of 35 respondents, the latent demand is estimated at 256,846 bundles. Compared to the number of bundles of German origin used for thatching in 2018 (126,594 bundles), this indicates an excess demand and a supply gap for reed of regional origin.

When asked whether thatchers or their employees promote reed of regional origin to their customers only 30% responded that they did (n = 46). For the thatchers denying the promotion of regional reed, the most common reason was an insufficient supply (50%) and the second one the poor quality of reed of regional origin (31%) (n = 31). The quality deficiencies specified consider too short and/or too soft reed (n = 4). All reasons given by thatchers for not promoting reed of regional origin are listed in the original wording in Appendix A Table A1.

Table 6 shows that the perceived quality of reed has an impact on the promotion of regional reed. A Fisher's Exact test showed a significant correlation between the promotion of regional reed and the assessment of the quality of reed of regional origin compared to reed from other sources ($p = 0.002$; n = 36).

Despite the reed of regional origin being perceived as inferior in some cases, 69% of thatchers who have so far not promoted reed of regional origin would generally be willing to offer more of it, 15% would be unwilling to do so, and 15% had no opinion on this question (n = 32). Of the thatchers who already promoted regional reed, 86% would be willing to offer even more and 14% had no opinion on the subject (n = 14).

Table 6. Relationship between quality assessment and promotion of thatching reed by responding thatching companies in Northern Germany.

Promotion of Thatching Reed of Regional Origin	Quality Assessment of Regional Reed Compared to Other Sources			Total
	Worse	Same	Better	
Yes	0	8	3	11
No	13	5	7	25
Total	13	13	10	36

3.9. Supply of Reed of Regional Origin

In order to check whether the supply of reed of regional origin is large enough to meet the current demand, the thatchers were asked whether sufficient reed of regional origin was available. Of the respondents (n = 45), 36% stated to have sufficient thatch of regional origin available, while 64% stated that the available thatch could not cover their orders. After a qualitative evaluation, the thatchers gave eight reasons why the demand for reed of regional origin could not have been met. The most common reason (23% of the respondents) was "Too little reed beds/declining stocks", "Nature conservation", and "No offer" (n = 28). All reasons given by the thatchers are listed as quotes in Appendix A Table A2.

According to the survey, four companies (8.5%) conduct reed harvesting (n = 4) in Northern Germany. Of the other companies, 12 (25.5%) harvested reed in former timers but gave it up in the 60s or 70s (n = 3), 80s or 90s (n = 3), or since 2000 (n = 6). One of the companies currently harvesting reed is located in Lower Saxony, two of the companies in Mecklenburg-Western Pomerania and one company in Schleswig-Holstein. The company in Lower Saxony also cultivated reed for this purpose, the other three harvested only existing natural reed beds. The companies that conducted own reed harvesting harvested a total of 54,256 bundles (M = 13,564, SD = 21,274) of reed in winter 2017/2018 (harvest period for 2018), of which 45,456 bundles (84%) were harvested by the company in Lower Saxony. Two of the companies did not state how many Euro bundle of reed they installed in total in 2018. In one of the companies the self-harvested bundles accounted for 10% of the total bundles installed, in the other the installed bundles only made up 40% of the self-harvested bundles.

3.10. Extrapolation of the Market Volume and the Markt Potential for Reed of Regional Origin

Based on the survey information, the results were extrapolated to the entire thatching market in Northern Germany. The focus was on the quantity and value of thatching reed and the market share and market potential for regional reed. According to the Kruskal–Wallis test, the hypothesis that distribution of all above reported variables are identical between Schleswig-Holstein, Lower Saxony, and Mecklenburg-Western Pomerania could not be rejected, except for three variables. These were the number of orders for renewed roofs and repairs and the price for thatch of non-German origin. Therefore, we consider it as justifiable to perform a simple extrapolation instead of a weighted one, assuming the whole sample distribution to represent the entire population (Table 7). The extrapolated point estimates are presented together with the 95% confidence intervals. Because the share of reed of German origin of 17% could be verified by external sources (see Section 3.4), the market share was taken as certain. All other variables were subjected to a calculation of sampling errors, i.e., estimating how far the population mean is likely to be from the sample mean.

Thus, we estimated a market volume of 3 ± 0.8 million bundles of reed in Northern Germany, where the majority of reed is installed by companies located in Schleswig-Holstein, followed by Mecklenburg-Western Pomerania, and Lower Saxony. The total market value of reed in sales prices is estimated at €11.6 ± 2.8 million.

Table 7. Estimated market volume and market potential of reed of regional origin in Northern Germany in 2018 (N = 141).

Item	Indicator, Unit	Calculation [b]	Northern German Market [b,c]
Market volume	Reed bundles [a], number	141 companies × 21,445 ± 5755 bundles per company	3,024,000 ± 811,000
	Value, €	Reed bundles of non-German origin × €3.90 ± 0.3 per reed bundle + reed bundles of German origin × €3.57 ± 0.3 per reed bundle	11,624,000 ± 2,756,000
Market volume for reed of regional or German origin	Reed bundles, number	141 companies × 21,445 ± 5755 bundles per company × share of reed of regional or German origin (0.17)	511,000 ± 137,000
	Value, €	Reed bundles of regional or German origin × €3.57 ± 0.3 per reed bundle	1,824,000 ± 515,000
Market potential for reed of regional or German origin	Reed bundles, number	Share of customers demanding reed of regional origin (0.34 ± 0.08) × total number of reed bundles	1,034,000 ± 367,000
	Value, €	Market potential for reed of regional or German origin in reed bundles × €3.57 ± 0.3 per reed bundle	3,692,000 ± 1,348,000
Excess demand or Supply gap for reed of regional or German origin	Reed bundles, number	Market potential for reed of regional or German origin−respective actual market volume	523,000 ± 392,000
	Value, €	Value of the market potential for reed of regional or German origin−respective actual market value	1,867,000 ± 1,407,000

Note: [a] Reed bundles refer to a Euro reed bundle. [b] All numbers are expected values for the whole population, where ± indicates the sampling error for a 95% confidence interval. [c] Numbers are rounded to values of thousands.

The market volume for regional or German reed in Northern Germany is estimated at 511,000 ± 137,000 bundles and at a market value of €1.8 ± 0.5 million. The market potential, however, is much higher as the final demand for regional reed suggests. Thus, we estimated a supply gap for reed of regional or German origin of 523,000 ± 392,000 bundles or €1.9 ± 1.4 million. If supplied at current quality and prices it is estimated that on average more than double the bundles could have been sold. However, these estimates are connected with substantial uncertainty.

4. Discussion

Thatchers are decisive actors in the reed value chain being responsible for both purchasing reed and thatching roofs for the house owners. Our survey among thatchers provides the first in-depth analysis of the market for thatching reed in Northern Germany. We determined the market volume of thatching reed in Northern Germany and assessed the market potential for reed of regional origin in quantitative and qualitative terms.

4.1. Current State and Development of the Reed Market in Northern Germany

For answering the first research question, we estimated the total market volume for thatching reed in Northern Germany and analyzed the market volume for the three different thatching services identified: (1) newly build roofs, (2) renewal, and (3) repair of existing roofs. The total market volume was estimated at around 3 ± 0.8 million bundles of reed with a monetary value at sales prices of €11.6 ± 2.8 million in 2018. These figures are an extrapolation, which is to be viewed under the fact that there were large differences between the surveyed companies. Few literature is available to verify the extrapolation.

The EU trade statistics depict general trends and interannual differences in reed trade between countries [15] but appear unsuitable for cross validation of the total market volume (in bundles) for a specific year. According to the extrapolated survey data about 2.5 ± 0.7 million bundles were imported. Converting the imports of 6367 tons of reed reported in EU trade statistic into bundles (assuming average weights of 4 kg, based on 3.2 kg dry mass per bundle (range: 2.4–5 kg) [43] and 15–18% water content in traded bundles) resulted in about 1.5 million bundles. The difference amounts to almost 1 million bundles for the point estimate and 0.3 to 1.7 million bundles for the 95% confidence interval. That reed quantities are not completely pictured by EU trade statistics may be linked to observation gaps for goods traded between EU member states, e.g., due to Intrastat reporting exemption thresholds [44]. Furthermore, bundles have a standard value for the circumference but not for the mass. Long (>1.90 m), medium long (>1.40 m), and short bundles are distinguished [25]. Extreme droughts experienced in Europe in 2016/2017 [45] may have affected the reed growth and led to shorter bundles with lower weight traded in 2018. Finally, reed may be stored and the year of purchase and of thatching may differ.

The calculated total market volume of 3 ± 0.8 million reed bundles, however, equals an earlier estimate of 3 million bundles made by the Society for reed quality assurance (QSR), which was based on information provided by reed traders [11]. Wichmann and Köbbing [15] identified further similar estimates of 2–3 million bundles for single periods between 1990 and 2013. A considerably higher value of 4.8 million bundles of reed needed per year in Northern Germany was mentioned in 1996 by the chairman of the thatcher guild Mecklenburg-Western Pomerania and published in Schäfer [46]. Fluctuations between the years [46] are mentioned as well as a decline of the reed market at the beginning of the 21st century due to observed cases of early decay of thatched roofs [11]. The recovery of the reed market stated by QSR [11] seems to have continued since the results of our survey suggest a slightly increased demand for thatching newly built houses in Northern Germany in the past 10 years (2008–2018). According to the conducted linear regression, the responding thatchers used only 24% of the reed for newly constructed roofs in 2018, but 59% for completely renewed roofs, and 17% for roof repairs. It is unknown, however, how many thatched roofs exist in Germany [11]. Furthermore, it cannot be assessed whether the number of thatched roofs increases due to newly built houses or decreases due to thatched houses being demolished or covered with a hard roof at the end of the lifetime of the soft thatched roof.

4.2. Origins of Reed and Development of Market Shares

The second research question addresses the origin of the reed used for thatching in Northern Germany. The survey results clearly show that most of the reed is imported from the European market (67%) and from China (16%). Only 17% of the reed bundles are from Germany. The calculated import shares were confirmed by EU trade statistics reporting 66% of reed imported from the European market and 17% from China. In an overview study of the European reed market, an import rate fluctuating around 80% from 1990 to 2013 was reported for Germany [15]. The import rate of 83% revealed by the survey fits well to these literature values. Imports continue to be at a high level and even might have increased slightly.

4.3. The Potential of Reed of Regional Origin

The third research question focuses on the market of reed of regional origin and factors influencing the demand and supply. The majority of the responding thatchers relates the term "regional" to their own federal state (28%) or even to their own district (26%). German reed is considered as being "regional" only by 33% of the respondents. Most of the German reed used by thatchers is indeed from their specific federal state (Table 3). The thatchers also indicated that on average a third of their customers asked about reed of regional origin, but the range was as wide as possible reaching from 0 to 100%. According to the extrapolation, the current market volume of reed from Germany is 511,000 ± 137,000 bundles with a monetary value of €1.8 ± 0.5 million. The market potential, based on the share of costumers asking for regional reed on their own, is about double (1 ± 0.4 million bundles, €3.7 ± 1.4 million), indicating an excess demand of 523,000 ± 392,000 bundles (€1.9± 1.4 million) not met by the current supply. Assuming an average yield of 500 bundles per hectare [19], this latent demand can be covered by an additional harvest area of 1046 ± 784 ha. Considering that 70% of the responding thatchers do not promote reed of regional origin, the potential market for reed of regional origin can be larger than calculated. The majority of thatchers who have not yet promoted reed of regional origin would generally be willing to do so (69%). The unavailability of regional reed was mentioned by 50% as the reason for not promoting regional reed and insufficient quality by 31%. Surprisingly, thatching reed from Germany is offered at a significant slightly lower price despite of the demand exceeding the supply. This result might indicate that although regional reed is preferred, final consumers are not willing to pay a higher price. Furthermore, lower prices might be connected with lower quality [47]. Quality issues were repeatedly reported by the surveyed thatchers as reasons for not promoting regional reed or for the inability to supply the demand of customers (see Tables A1 and A2). Nevertheless, thatchers were quite divided in their assessments and some consider regional reed as of superior quality (see Figure 4). In particular, thatchers who harvest reed were convinced of the superior quality. Although there is some scientific literature on the quality of reed for thatching from different provinces, the results show the huge variability and are overall inconclusive about the quality of reed of different origins [48,49].

4.4. Potential and Obstacles of Cultivating Reed

It can be concluded that there is a demand for more and above all more high-quality reed of regional origin. Cultivating reed may improve both quantity and quality of regional reed for thatching. Thus, cultivating thatching reed is one promising and climate-smart alternative to drained agricultural peatlands. Growing reed on rewetted peatlands can generate climate benefits in several ways: (a) minimizing CO_2 emissions from peat oxidation [50], (b) acting as strong CO_2 sink [51] due to carbon-capture and long-term storage in belowground biomass and peat formation, (c) using reed for replacing fossil resources, e.g., avoided emissions caused by energy use in roof tile production, and (d) (temporal) carbon-capture and storage if harvested aboveground biomass is used as long-life building material.

In terms of area demand, however, 6000 ± 1600 ha with an average yield of 500 bundles per hectare [15] would be sufficient to produce even all 3 ± 0.8 million bundles of the current total market. Considering a surplus area, e.g., for buffering for harvest failures, a maximum area of 10,000 ha is needed. Applying national GHG emission factors (including emission of CO_2, CH_4, N_2O) for drained cropland (40.4 t CO_2-eq.), drained grassland (31.7 t CO_2-eq.) and rewetted sites (5.5 t CO_2-eq [52]), the annual saving due to minimized peat oxidation for 10,000 ha could be 260,000 to 350,000 t CO_2-eq. In relation to total emissions of about 45 Mio t CO_2-eq from agricultural used drained peatlands in Germany [52], this saving can only be a small component. Other biomass utilization options and further crops need to be investigated to provide economically viable paludiculture options [19] for about 383,000 ha of arable land and 852,000 ha of grassland on drained organic soils [53] in Germany.

The cultivation of reed may range from shifting the harvest season from summer to winter, over improved water management, the planting of pre-cultivated seedlings for stand establishment, up to the selection of provenances, genotypes, or even breeding for improved reed quality. So far, winter harvested reed stands in Germany are not eligible for direct payment under the EU Common Agricultural Policy [54]. Therefore, it is not surprising that reed cutters report wet grassland to be mown by the land manager in summer (and thus impeding a winter harvest for thatching) just for generating EU subsidies despite of a lack of utilization for the biomass. Negotiations on the new CAP post 2020 include proposals for considering paludiculture as eligible for agricultural payments in the future, which would eliminate a major obstacle of reed cultivation. Another factor is the need for special harvesting equipment adapted to the low bearing capacity of reed stands and equipped with a specific mowing (and cleaning) device [55]. The purchase of such a machine is economically feasible only with a certain minimum size of harvesting area. Our results showed, however, that the current reed harvesting area is limited (Table A2: not available, too small, very restricted use, nature conservation). Several pilot trials proved the feasibility of planting reed for establishing a reed stand in Great Britain [56], the Netherlands [16], and Germany [57,58], and practical experience of the commercial harvest of planted reed stands is available. Research on how to achieve and improve thatching qualities of reed cultivated on rewetted peatlands is still in progress.

4.5. Limitations of the Study

When evaluating the results and the extrapolation, it should be kept in mind that with a participation rate of 33%, the situation of 94 thatching companies in Northern Germany remains unknown. It should also be noted that due to individual unanswered questions, the response rate of 33% was not met for all questions. These nonresponses reduced the effective sample size and unavoidably increased the sampling error. Based on the assumption that nonresponses were completely random, confidence intervals for major extrapolated variables could be computed. However, nonsampling errors might have occurred. The participation was determined by the willingness of the thatchers to take part in the survey. It is conceivable that responses were given by larger companies that had the human resources or by thatchers who were already interested in the topic of "regionality". This was attempted to be reduced by avoiding the topic of regionality at the beginning and in the cover letter of the questionnaire. Overall, it can be concluded that, based on the target group and the survey design, a response rate of 33% represents a satisfactory effective sample size suitable to make valid statements, which was demonstrated by the comparison with trade data and literature values. It can therefore be assumed that despite all uncertainties, overall a good overview of the market for reed in Northern Germany could be given. Limitations concern the concept of "regional reed", which may be defined differently by thatchers and house owners. In addition, the question on prices paid for a reed bundle by the end consumer lacks a specification on gross and net values so that the stated prices must be viewed with caution. In conclusion, it is pointed out that the present work is limited to the perspective of thatchers. Addressing further actors of the reed value chain such as reed cutters, traders of thatching reed, or the owners of thatched house can provide further insights into the reed market.

5. Conclusions

The results provide a detailed picture of the reed market in Northern Germany and quantify the market potential for reed of regional origin. The lacking supply of regional reed concerns not only the quantity but also the quality. The survey revealed a further decline in domestic reed harvesting and conflicts with nature conservation targets. Considering the large areas of drained peatlands and wetlands used for agriculture, rewetting already a very small share of it for reed cultivation would allow to improve the regional availability of reed as traditional ecological roofing material and simultaneously reduce GHG emissions. Further investigations are needed on the quality of reed cultivated in paludiculture. A similar situation can be assumed for other European countries, as the Netherlands, the UK, and Denmark, which share the tradition of thatching houses with reed, have large areas of drained wetlands and import up to 85% of their reed.

Author Contributions: Conceptualization, L.B., S.W. and V.B.; methodology, L.B., S.W. and V.B.; validation, L.B., S.W. and V.B.; formal analysis, L.B., V.B.; investigation, L.B.; resources, S.W., V.B.; data curation, L.B., S.W., V.B.; writing—original draft preparation, L.B., V.B. and S.W.; writing—review and editing, S.W., V.B.; visualization, S.W., V.B.; supervision, S.W., V.B.; project administration, S.W.; funding acquisition, S.W., V.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Bundesministerium für Ernährung und Landwirtschaft | Fachagentur Nachwachsende Rohstoffe, grant number FKZ 22026017.

Acknowledgments: We thank all thatchers for participating in the survey and Stephan Busse for creating the map on sampled and responding thatching companies.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Reasons why reed of regional origin was not promoted, full answers.

Participant ID	Response
1	Too little available, culm length too short (hearsay)
2	Quality is sometimes not sufficient
3	Quality is worse than reed from Ukraine and China
4	Because thatch from other countries is also good, but should be in the same latitude
9	Because it is not available
11	Amount offered too small
12	Too few with good quality available
13	Because there is hardly anything and because the greens throw us sticks between the legs
14	Quality is comparable, and the price is more important to the customer
16	Most of the reed goes to Holland, the rest is personal consumption
17	It does not depend on the origin, but on the usability on the respective roof or on the respective conditions
19	Insufficient quantity available
20	Because not enough reed comes from Germany
21	There is hardly any local thatch, so I cannot promote it
23	Nothing on the market, not available
24	Unfortunately no longer—product data sheet
25	There is too little
27	In principle, it is only available to a very limited extent
28	Does not meet my expectations, mostly too short and very soft
30	Too little regional reed

Table A1. *Cont.*

Participant ID	Response
32	Since there is no thatch on the market!
34	Because there is none
35	I don't have a supplier/trader for regional reed
37	Not good quality
38	Reed that is too short and too fine
41	No offer
42	Too much effort
43	Because the quality of reed bundles has not been satisfactory in recent years
46	Because German reed that grows up in the Weser river in algae and reed from S-H is too soft.
47	It is not possible to buy the quantity

Note: Only those participants are listed who have given an answer.

Table A2. Reasons why there wasn't enough reed of regional origin to meet demand, full answers.

Participant ID	Response
1	Not enough harvesting areas, nature conservation
4	Because too little thatch is harvested in Germany
8	Depends on the size of the building and staff (construction project)
12	A lot of regional thatch is not offered in the quality that it meets the "technical rules for roofing with thatch"
13	1. You have to apply for harvesting permits 1 year in advance 2. You then don't know whether it is possible to mow (frost). What then: 3. would be throwing money out of the window. 4. It is very difficult to meet the requirements
15	Not enough areas for harvesting
17	Applies to us, not to the industry. Not enough reed is allowed to be harvested for the entire needs of the regional branch.
19	Insufficient area available or no harvesters
20	Because too little is harvested or not enough
21	There is only one person cultivating reed here and the amount is limited
23	Nothing on the market, not available
24	Rent too high for German thatchers
25	Politically that is probably what is wanted
27	Existing reed beds (areas) may only be used very restrictively, see guidelines for reed harvesting in MV
28	No or too small harvest areas -> NABU and nature conservation
30	There is not enough regional thatch on the market
31	Too little land to harvest
32	Because hardly any thatch is harvested!
34	The reed beds have declined sharply
35	Don't know who is supplying me with it
38	Because there is too little land for harvesting
39	Because more and more "falls" towards nature conservation

Table A2. *Cont.*

Participant ID	Response
40	Too little reed harvesting
41	Location dependent
42	Hardly or not at all offered by traders
43	There are only small quantities of good quality—you have to secure a batch quickly or in due time. Often the required quantity is only sufficient for 1–2 orders for new roofs.
46	Areas are banned or not redistributed—stock is decreasing
47	You would need relationships

Note: Only those participants are listed who have given an answer.

References

1. Rodewald-Rudescu, L. *Das Schilfrohr. (Phragmites Communis Trinus)*; Schweizerbart: Stuttgart, Germany, 1974; ISBN 9783510400386.
2. Haslam, S.M. *A Book of Reed: (Phragmites Australis (Cav.) Trin. ex Steudel, Phragmites Communis Trin.)*; Forrest Text: Cardigan, UK, 2010; ISBN 978-0-9564692-0-5.
3. Kiviat, E. Ecosystem services of Phragmites in North America with emphasis on habitat functions. *AoB Plants* **2013**, *5*, plt008. [CrossRef]
4. Köbbing, J.F.; Thevs, N.; Zerbe, S. The utilisation of reed (*Phragmites australis*): A review. *Mires Peat* **2013**, *13*, 1–14.
5. Brix, H.; Ye, S.; Laws, E.A.; Sun, D.; Li, G.; Ding, X.; Yuan, H.; Zhao, G.; Wang, J.; Pei, S. Large-scale management of common reed, Phragmites australis, for paper production: A case study from the Liaohe Delta, China. *Ecol. Eng.* **2014**, *73*, 760–769. [CrossRef]
6. Köbbing, J.F.; Beckmann, V.; Thevs, N.; Peng, H.; Zerbe, S. Investigation of a traditional reed economy (*Phragmites australis*) under threat: Pulp and paper market, values and Netchain at Wuliangsuhai Lake, Inner Mongolia, China. *Wetl. Ecol. Manag.* **2016**, *24*, 357–371. [CrossRef]
7. Schattke, W. *Das Reetdach. Natürliches Wohnen unter Sanftem Dach—von der Urzeit bis Heute, 3. Aufl.*; Christians Verlag: Hamburg, Germany, 1992; ISBN 3-7672-1140-8.
8. German UNESCO Commission. *German Inventory of Intangible Cultural Heritage*; German UNESCO Commission: Bonn, Germany, 2019; ISBN 978-3-940785-97-8.
9. Deutsche UNESCO-Kommission. Reetdachdecker-Handwerk. Available online: https://www.unesco.de/kultur-und-natur/immaterielles-kulturerbe/immaterielles-kulturerbe-deutschland/bundesweites-43 (accessed on 9 April 2020).
10. Haslam, S.M. Early decay of *Phragmites* thatch: An outline of the problem. *Aquat. Bot.* **1989**, *35*, 129–132. [CrossRef]
11. QSR—Gesellschaft zur Qualitätssicherung Reet mbH. *Reet als Dacheindeckungsmaterial Qualitätssicherung und -Erhaltung eines Baustoffs aus Nachwachsenden Rohstoffen. Bericht zum Forschungsvorhaben der Deutschen Bundesstiftung Umwelt*. 2008. Available online: https://www.dbu.de/OPAC/ab/DBU-Abschlussbericht-AZ-25018.pdf (accessed on 14 December 2020).
12. Schrader, M. *Reet & Stroh als historisches Baumaterial. Ein Materialleitfaden und Ratgeber*; Anderweit Verlag GmbH: Suderburg-Hösseringen, Germany, 1998.
13. Bartels, O. Das Scheunentrio von Prerow. Ausgezeichnete Baukultur mit Vorbildcharakter. *Deutsches Architektenblatt* **2014**, *9*, 23–25. Available online: https://www.architektenkammer-mv.de/media/dab-ausgaben-2014/dab-mv-09-14final.pdf (accessed on 14 December 2020).
14. The Contemporist. 12 Examples of Modern Houses and Buildings That Have a Thatched Roof. Available online: https://www.contemporist.com/modern-houses-that-have-thatched-roof/ (accessed on 14 December 2020).
15. Wichmann, S.; Köbbing, J.F. Common reed for thatching—A first review of the European market. *Ind. Crop. Prod.* **2015**, *77*, 1063–1073. [CrossRef]

16. Geurts, J.J.M.; van Duinen, G.-J.A.; van Belle, J.; Wichmann, S.; Wichtmann, W.; Fritz, C. Recognize the high potential of paludiculture on rewetted peat soils to mitigate climate change: Position Paper. *J. Sustain. Org. Agric. Syst.* **2019**, *69*, 5–8.
17. Wichtmann, W.; Schröder, C.; Joosten, H. Paludikultur als integrative Systemlösung. In *Paludikultur: Klimaschutz—Biodiversität—Regionale Wertschöpfung*; Schweizerbart: Stuttgart, Germany, 2016; pp. 1–2.
18. Greifswald Mire Centre; National University of Ireland Galway; Wetlands International European Association. Peatlands in the EU. Common Agricultural Policy (CAP) after 2020. Position Paper—(Version 4.8). 2020. Available online: https://greifswaldmoor.de/files/dokumente/Infopapiere_Briefings/202003_CAP%20Policy%20Brief%20Peatlands%20in%20the%20new%20EU%20Version%204.8.pdf (accessed on 14 December 2020).
19. Wichmann, S. Commercial viability of paludiculture: A comparison of harvesting reeds for biogas production, direct combustion, and thatching. *Ecol. Eng.* **2017**, *103*, 497–505. [CrossRef]
20. Tanneberger, F.; Schröder, C.; Hohlbein, M.; Lenschow, U.; Permien, T.; Wichmann, S.; Wichtmann, W. Climate Change Mitigation through Land Use on Rewetted Peatlands—Cross-Sectoral Spatial Planning for Paludiculture in Northeast Germany. *Wetlands* **2020**. [CrossRef]
21. Tanneberger, F.; Appulo, L.; Ewert, S.; Lakner, S.; Brolcháin, N.Ó.; Peters, J.; Wichtmann, W. The Power of Nature-Based Solutions: How Peatlands Can Help Us to Achieve Key EU Sustainability Objectives. *Adv. Sustain. Syst.* **2020**, 2000146. [CrossRef]
22. Hellin, J.; Meijer, M. Guidelines for Value Chain Analysis. 2006. Available online: http://www.fao.org/fileadmin/templates/esa/LISFAME/Documents/Ecuador/value_chain_methodology_EN.pdf (accessed on 14 December 2020).
23. Zamora, E.A. Value Chain Analysis: A Brief Review. *Asian J. Innov. Policy* **2016**, *5*, 116–128. [CrossRef]
24. Teuber, R. Geographical Indications of Origin as a Tool of Product Differentiation: The Case of Coffee. *J. Int. Food Agribus. Mark.* **2010**, *22*, 277–298. [CrossRef]
25. Zentralverband des Deutschen Dachdeckerhandwerks—Fachverband. *Produktdatenblatt für Reet*, 12th ed.; Verlagsgesellschaft Rudolf Müller GmbH & Co. KG.: Köln, Germany, 2019; ISBN 978-3-481-03993-6.
26. Wirthgen, A. Consumer, retailer, and producer assessments of product differentiation according to regional origin and process quality. *Agribusiness* **2005**, *21*, 191–211. [CrossRef]
27. Hague, P.; Harrison, M.; Cupman, J.; Truman, O. *Market Research in Practice. An Introduction to Gaining Greater Market Insight*, 3rd ed.; Kogan Page: London, UK, 2016; ISBN 9780749475864.
28. Baur, N.; Blasius, J. (Eds.) *Handbuch Methoden der Empirischen Sozialforschung*; Springer Fachmedien Wiesbaden; Springer: Wiesbaden, Germany, 2019; ISBN 978-3-658-21308-4.
29. Groves, R.M.; Fowler, F.J.; Couper, M.; Lepkowski, J.M.; Singer, E.; Tourangeau, R. *Survey Methodology*, 2nd ed.; Wiley: Hoboken, NJ, USA, 2009; ISBN 9780470465462.
30. Schnell, R.; Hill, P.B.; Esser, E. *Methoden der Empirischen Sozialforschung, 8., unveränd. Aufl.*; Oldenbourg: München, Germany, 2008; ISBN 9783486587081.
31. Särndal, C.-E.; Lundström, S. *Estimation in Surveys with Nonresponse*; Wiley: Hoboken, NJ, USA, 2005; ISBN 9780470011331.
32. Siebert, C.F.; Siebert, D.C. *Data Analysis with Small Samples and Non-Normal Data. Nonparametrics and Other Strategies*; Oxford University Press: New York, NY, USA, 2018; ISBN 9780199391509.
33. Janssen, J.; Laatz, W. *Statistische Datenanalyse mit SPSS*, 9th ed.; Springer Gabler: Berlin/Heidelberg, Germany, 2017.
34. Rea, L.M.; Parker, R.A. *Designing and Conducting Survey Research. A Comprehensive Guide*, 4th ed.; Jossey-Bass: San Francisco, CA, USA, 2014; ISBN 9781118767030.
35. Hughes, I.; Hase, T.P.A. *Measurements and Their Uncertainties. A Practical Guide to Modern Error Analysis*; Oxford University Press: Oxford, UK, 2010; ISBN 1282732269.
36. Mayring, P. *Qualitative Inhaltsanalyse. Grundlagen und Techniken, 12., überarb. Aufl.*; Beltz: Weinheim, Germany, 2015; ISBN 3407257309.
37. Wirtz, M.; Kutschmann, M. Analyzing Interrater Agreement for Categorical Data Using Cohen's Kappa and Alternative Coefficients. *Rehabilitation* **2007**, *46*, 370–377. [CrossRef] [PubMed]
38. Landis, J.R.; Koch, G.G. The Measurement of Observer Agreement for Categorical Data. *Biometrics* **1977**, *33*, 159–174. [CrossRef]
39. European Union. Eurostat. Available online: https://ec.europa.eu/eurostat/web/international-trade-in-goods/data/database (accessed on 28 October 2020).

40. MeinDach GmbH. Mein Dach. Available online: https://www.meindach.de/ratgeber/was-kostet-ein-dach/ (accessed on 17 April 2020).
41. Reetdachdeckerei Ohm. o.T. Available online: https://www.reetdachdeckerei-ohm.de/reetdach.html (accessed on 17 April 2020).
42. Zentralverband des Deutschen Dachdeckerhandwerks—Fachverband. *Fachregeln für Dachdeckungen mit Reet*, 12th ed.; Verlagsgesellschaft Rudolf Müller GmbH & Co. KG.: Köln, Germany, 2019.
43. Dahms, T.; Oehmke, C.; Kowatsch, A.; Abel, S.; Wichmann, S.; Wichtmann, W.; Schröder, C. *Halmgutartige Festbrennstoffe aus Nassen Mooren. Paludi-Pellets-Broschüre*; Universität Greifswald: Greifswald, Germany, 2017.
44. European Union. *National Requirements for the Intrastat System*, 2018 ed. 2017. Available online: https://ec.europa.eu/eurostat/documents/3859598/8512202/KS-07-17-102-EN-N.pdf/736c4a50-c240-4144-b087-4fa6aece8ee0 (accessed on 14 December 2020).
45. García-Herrera, R.; Garrido-Perez, J.M.; Barriopedro, D.; Ordóñez, C.; Vicente-Serrano, S.M.; Nieto, R.; Gimeno, L.; Sorí, R.; Yiou, P. The European 2016/17 Drought. *J. Clim.* **2019**, *32*, 3169–3187. [CrossRef]
46. Schäfer, A. Schilfrohrkultur auf Niedermooren—Rentabilität des Anbaus und der Ernte von Phragmites Australis. *Archiv für Naturschutz und Landschaftsforschung* **1999**, *38*, 193–216.
47. Wolinsky, A. Prices as signals of product quality. *Rev. Econ. Stud.* **1983**, *50*, 647–658. [CrossRef]
48. Wöhler-Geske, A.; Moschner, C.R.; Gellerich, A.; Militz, H.; Greef, J.-M.; Hartung, E. Provenances and properties of thatching reed (*Phragmites australis*). *Landbauforschung* **2016**, *66*, 1–10.
49. Boar, R.R.; Kirby, J.J.H.; Leeming, D.J. Variations in the quality of the thatching reed Phragmites australis from wetlands in East Anglia, England. *Geol. Soc. Lond. Spec. Publ.* **1999**, *163*, 145–151. [CrossRef]
50. Günther, A.; Huth, V.; Jurasinski, G.; Glatzel, S. The effect of biomass harvesting on greenhouse gas emissions from a rewetted temperate fen. *GCB Bioenergy* **2015**, *7*, 1092–1106. [CrossRef]
51. Minke, M.; Augustin, J.; Burlo, A.; Yarmashuk, T.; Chuvashova, H.; Thiele, A.; Freibauer, A.; Tikhonov, V.; Hoffmann, M. Water level, vegetation composition, and plant productivity explain greenhouse gas fluxes in temperate cutover fens after inundation. *Biogeosciences* **2016**, *13*, 3945–3970. [CrossRef]
52. Tiemeyer, B.; Freibauer, A.; Borraz, E.A.; Augustin, J.; Bechtold, M.; Beetz, S.; Beyer, C.; Ebli, M.; Eickenscheidt, T.; Fiedler, S.; et al. A new methodology for organic soils in national greenhouse gas inventories: Data synthesis, derivation and application. *Ecol. Indic.* **2020**, *109*, 105838. [CrossRef]
53. Umweltbundesamt. *Berichterstattung unter der Klimarahmenkonvention der Vereinten Nationen und dem Kyoto-Protokoll 2019. Nationaler Inventarbericht zum Deutschen Treibhausinventar 1990–2017*; Climate change 23/2019; Umweltbundesamt: Germany, 2019; Available online: https://www.umweltbundesamt.de/publikationen/berichterstattung-unter-der-klimarahmenkonvention-4 (accessed on 14 December 2020).
54. Kölsch, L.; Witzel, S.; Czybulka, D.; Fock, T. Agricultural policy. In *Paludiculture—Productive Use of Wet Peatlands: Climate Protection—biodiversity—Regional Economic Benefits*; Wichtmann, W., Schröder, C., Joosten, H., Eds.; Schweizerbart Science Publishers: Stuttgart, Germany, 2016; pp. 149–152, ISBN 9783510652839.
55. Wichmann, S.; Dettmann, S.; Dahms, T. Agricultural machinery for wet areas. In *Paludiculture—Productive Use of Wet Peatlands: Climate Protection—Biodiversity—Regional Economic Benefits*; Wichtmann, W., Schröder, C., Joosten, H., Eds.; Schweizerbart Science Publishers: Stuttgart, Germany, 2016; pp. 64–70, ISBN 9783510652839.
56. Hawke, C.; José, P. *Reedbed Management for Commercial and Wildlife Interests*; Royal Society for the Protection of Birds: Sandy, UK, 1996; ISBN 0903138816.
57. Timmermann, T. Anbau von Schilf (*Phragmites australis*) als ein Weg zur Sanierung von Niedermooren—Eine Fallstudie zu Etablierungsmethoden, Vegetationsentwicklung und Konsequenzen für die Praxis. *Archiv für Naturschutz und Landschaftsforschung* **1999**, *33*, 111–143.
58. Tschoeltsch, S. *Reet: Vom Anbau bis zum Dach. Das Reetprojekt aus der Eider-Treene-Sorge Niederung*; Verein zur Förderung der Kulturlandschaft e.V.: Horstedt, Germany, 2008.

Paper IV

Wichmann, S., Prager, A. & Gaudig, G. (2017)

Establishing *Sphagnum* cultures on bog grassland, cut-over bogs, and floating mats: procedures, costs and area potential in Germany.

Mires and Peat, 20 (3): 1–18.

Establishing *Sphagnum* cultures on bog grassland, cut-over bogs, and floating mats: procedures, costs and area potential in Germany

S. Wichmann, A. Prager and G. Gaudig

Institute of Botany and Landscape Ecology, Ernst Moritz Arndt University of Greifswald,
Partner in the Greifswald Mire Centre, Germany

SUMMARY

Sphagnum biomass is valued as a high-quality constituent of horticultural growing media. The cultivation of *Sphagnum* (peatmoss) was tested successfully on peat soil and on artificial mats floating on acidic water bodies. But whether Sphagnum farming is economically feasible is unclear. Drawing on experience gained during four research projects in Germany we compared the procedures, costs and area potential for establishing large-scale *Sphagnum* cultures. Establishment costs were clearly lower for soil-based cultivation (€8.35 m^{-2} to €12.80 m^{-2}) than for water-based cultivation (€17.34 m^{-2} to €21.43 m^{-2}). Relating costs to the predicted dry mass yield over the total cultivation time resulted in values of €1,723 t^{-1} on cut-over bog, €2,646 t^{-1} on former bog grassland, €9,625 t^{-1} on floating mats without pre-cultivation and €11,833 t^{-1} on pre-cultivated *Sphagnum* mats. The high production costs of the mats (without pre-cultivation 54 % and with pre-cultivation 63 % of total costs) resulted in the highest overall costs. In the case of soil-based *Sphagnum* cultures, the costs of purchasing *Sphagnum* diaspores were most influential (on bog grassland 46 % and on cut-over bog 71 % of total costs). The lowest costs relate to cut-over bog because of the smaller effort required for site preparation compared to taking off the topsoil of former bog grassland and the limited costs for the assumed irrigation system. In the case of former bog grassland, the high investment costs for the project-specific automatic water management boosted the establishment costs. Taking into account potential savings on the irrigation system and the high area potential, bog grassland emerges as the most promising land category for Sphagnum farming in Germany.

KEY WORDS: cost assessment, degraded bogs, growing media, paludiculture, Sphagnum farming

INTRODUCTION

Sphagnum biomass is regarded as a high-quality constituent of horticultural growing media (Emmel 2008, Oberpaur *et al.* 2010, Blievernicht *et al.* 2013) and is suitable for a wide range of additional applications (Zegers *et al.* 2006).

'Wild' *Sphagnum* is harvested in countries with extensive natural peatlands (*e.g.* Finland; Reinikainen *et al.* 2012) or *Sphagnum*-dominated (secondary) wetlands ('pomponales' in Chile; Díaz *et al.* 2008, Domínguez 2014). In countries where drainage has degraded almost all of the domestic peatland area, such as Germany (98 %) and The Netherlands (95 %) (Barthelmes 2016), the few bogs that are still covered by natural vegetation are strictly protected. Under these circumstances, the cultivation of *Sphagnum* ('Sphagnum farming') can provide *Sphagnum* biomass for peatland restoration (Money 1994) and as a renewable substitute for slightly decomposed 'white' peat in horticultural applications (Gaudig *et al.* 2014). Additionally, a mosaic of land- and water-based *Sphagnum* (peatmoss) cultivation has been proposed as a vision for sustainable use of a bog landscape that has been drained for agriculture and peat cutting up to the present time (Figure 1, Gaudig *et al.* 2014).

Pilot studies have demonstrated the practical feasibility of establishing *Sphagnum* cultures on former bog grassland (Joosten *et al.* 2013), cut-over bogs (Kamermann & Blankenburg 2008, Gaudig *et al.* 2017), and mats floating on acidic water bodies created by the extraction of peat, sand, and lignite (Joosten 2010; Blievernicht *et al.* 2011, 2012). However, the economic feasibility of *Sphagnum* cultivation and the preconditions for large-scale implementation have not yet been investigated.

This article provides a first assessment of the cost of establishing commercial *Sphagnum* cultures at the three types of production site, compares the relevant establishment procedures, and analyses options for and constraints on Sphagnum farming.

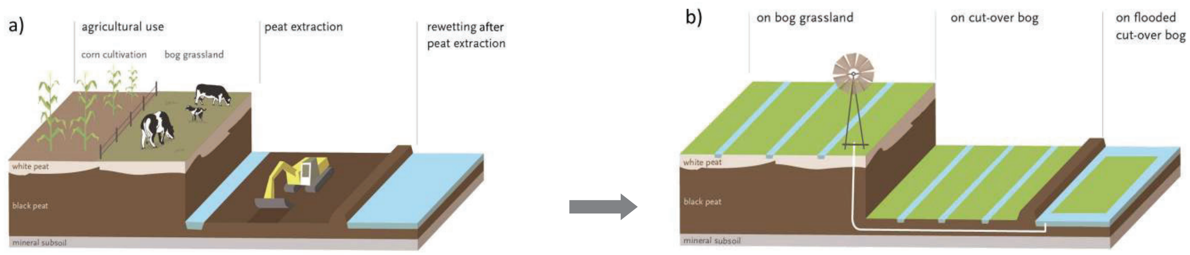

Figure 1. Mosaics of a) current land use on degraded bogs in NW Germany and b) *Sphagnum* cultures after rewetting (after Gaudig *et al.* 2014).

METHODS

Sphagnum farming is a new land use option. In contrast to conventional agricultural production methods, there are no established standard procedures or standard cost data available. Therefore, our cost assessment was conducted in two steps: a first qualitative step defining how *Sphagnum* cultures are established and which costs have to be considered; and a second quantitative step determining, for instance, the amount of time required and costs *per* hour of operating the machinery. Our cost calculations were based on experience from four research projects that aimed to establish *Sphagnum* cultures in Germany, on peat soil and artificial floatable mats (Table 1).

The MOOSGRÜN pilot trial was conducted on an area of approximately 4 ha of former bog grassland with a net production area of 20,268 m², making it possible to test mechanical establishment procedures and collect real-life data. We used daily time sheets to document the hours of labour and machinery provided by the industrial project partner for the individual work steps and compiled the invoices for purchase of materials and services provided by external enterprises.

The small pilot trial on cut-over bog (TORFMOOS) did not include cost assessments. However, on the basis of long-term experience of preparing cut-over sites for rewetting and restoration, it was possible to identify procedures and derive machinery costs for commercial upscaling. In order to create conditions favouring bog regeneration, peat companies in Lower Saxony are required to: (a) leave a waterlogging layer of at least 0.5 m of highly decomposed peat (H > 7, degree of humification according to von Post 1924); (b) create flat polders with surrounding surface bunds to retain precipitation; and (c) install outlets for surplus water (Blankenburg 2004, MU 2011). Additionally, some costs were assessed according to the trial on former bog grassland (MOOSGRÜN). The calculation was conducted for a fictional site of ~ 3 ha with a net production area of 20,000 m².

The first cost calculation for Sphagnum farming on floating mats was based on small trials and assumptions (MOOSFARM, reported in Joosten 2010). For this article, previous work has been revised in the light of experience gained by the practice partners in PROSUGA, when floatable mats were produced at industrial scale and successfully tested on man-made water bodies with an overall area of > 2,000 m².

The calculations encompassed site preparation or mat production and the establishment of the *Sphagnum* cultures. Planning costs (*e.g.* site identification, permissions) and costs of further management, maintenance, harvesting, *etc*. were not addressed. Generally, all enterprises involved in the projects supported our calculations by providing data on the costs of labour, machinery, investment and mat production. The price level refers to the year 2011, when field experiments were established on bog grassland and on floating mats at larger scale. For comparability, all costs were allocated to the net production unit, *i.e.* € *per* m² of *Sphagnum* lawn, and related to the harvestable amount of biomass.

Because *Sphagnum* is perennial, we assessed yields over the possible total cultivation time and conducted dynamic investment calculations. In addition to the initial establishment costs (E) in the first year ($t = 0$) we considered the intermediate costs (I) of some re-establishment occurring at a later time (t) and discounted costs back to present values (PV) with interest rate (i) (Equation 1). The present values of establishment costs were spread over the expected total cultivation time (T) and expressed as annuities (A), *i.e.* constant annual values (Equation 2).

Table 1. Main features of *Sphagnum* culture pilot trials conducted within four German research projects (2004–2015).

Medium	Field site	Net production area (m^2)	Cost assessment	Project name (duration)
peat soil, highly decomposed (black peat)	cut-over bog (Ramsloh, Lower Saxony)	1,260	NO not included	TORFMOOS (2004–2007)
floating mats	several water bodies (resulting from peat, sand or lignite extraction)	230	YES assumptions	MOOSFARM (2007–2010)
floating mats	several water bodies (resulting from peat or lignite extraction)	2,030	NO not included	PROSUGA (2010–2013)
peat soil, slightly decomposed (white peat)	former bog grassland (Rastede, Lower Saxony)	20,268[a]	YES field data	MOOSGRÜN (2010–2015)

[a]The total pilot area of 4 ha included infrastructure such as causeways and irrigation ditches.

$$PV = E + \sum_{t=1}^{T} \frac{I_t}{(1+i)^t} \quad [1]$$

$$A = PV * \frac{(1+i)^T * i}{(1+i)^T - 1} \quad [2]$$

After assessing the procedures and costs for establishing *Sphagnum* cultures, we looked at the potential for upscaling pilots in Germany. Based on literature, we assessed the area potential for commercial Sphagnum farming on former bog grassland, on cut-over bogs, and on acidic water bodies.

RESULTS

Procedures for establishing *Sphagnum* cultures

Cultures on bog grassland

The soil-based Sphagnum farming site consists of three elements: *Sphagnum* production strips, narrow ditches for irrigation around each production strip, and bunds used as causeways. Before planning and preparing the site, one of two types of production system (PS) must be chosen (Figure 2). The first involves the use of adapted harvesting machinery that can drive onto the wet *Sphagnum* production strips without damaging them so that fewer causeways are needed and *Sphagnum* production strips can occupy a larger share of the total field area (PS 1; Figure 2 a). The second type of production system (PS 2; Figure 2 c) involves the use of an excavator with a mowing bucket for management and harvesting. The maximum width of the production strips is determined by the maximum operating range of the excavator arm from the causeway. The width of 10 m also ensures sufficient lateral water supply from the ditches to the peatmoss in the middle of the strips

Setting up the pilot trial on bog grassland at Rastede (Lower Saxony, NW Germany; Table 1) consisted of two phases: (a) preparing the site; and (b) initiating the *Sphagnum* culture (*cf.* Table 2). A tracked bucket excavator (Komatsu PC 160, working width 250 cm, tracks 2 × 130 cm) was used for all construction work and an adapted snow groomer equipped with a manure spreader was used for the ‘seeding’ work.

The irrigation system allowed us to control the water table and water inflow electronically, and to monitor the trial remotely *via* the internet. The automatic water management system was expected to reduce the need for inspection visits, provide data for hydrological monitoring, and ensure a sufficient water supply. To operate the pump, valves and control centre, the field site had to be connected to an electrical power supply. Thus, in the case of the pilot trial, construction work included the installation of approximately 400 m of underground cable connecting to the national power grid at the nearest farmyard, with horizontal drilling for a culvert passing beneath the major runoff ditch.

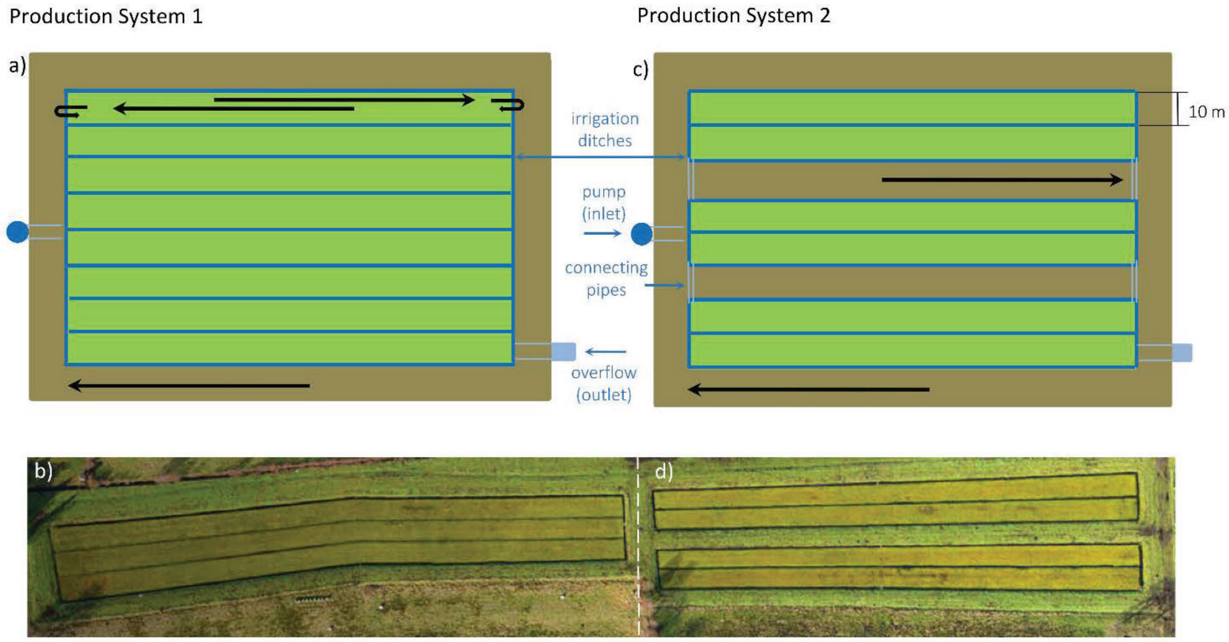

Figure 2. Soil-based *Sphagnum* culture (plan views). Production System 1 (PS 1) requires machines that can be driven (black arrows) onto the *Sphagnum* production strips (green), despite their low bearing capacity; the causeways (brown) provide a turning area for the machines and allow the transport of harvested biomass: a) schematic illustration, b) field experiment with three neighbouring production strips. Production System 2 (PS 2) provides more causeways for weed control machinery, moss harvesting and biomass transport: c) schematic illustration (following Wichmann *et al.* 2014), d) field experiment with 2 × 2 production strips.

Cultures on cut-over bogs

The work steps required to establish *Sphagnum* cultures on cut-over bogs are similar to those described for bog grassland (Table 2). The main differences relate to the initial site conditions. The even surface of bare peat that remains after milled peat extraction means that less effort is required to prepare the site. Instead of removing the topsoil, it is sufficient to adjust small height differences. A tracked vehicle equipped with a blade smooths the surface and removes peat for bunding, as is common in peatland restoration work (Figure 3a). An excavator shapes the bunds, which are used as causeways. A minimum height of 1 m is suggested for main bunds when restoring excavated sites (Blankenburg 2004).

It can be assumed that excavated sites are generally too distant from settled areas to allow a connection to the power grid. The field trial in Ramsloh (Table 1) was irrigated with ditch water using a wind pump. Water retention basins or wells might be necessary on large sites. To ensure a sufficient water supply in periods with little wind and high evaporation, investment costs for a mobile electric pump and generator (emergency power unit) were included. In the Ramsloh trial, underground irrigation pipes were installed every 5 m at a depth of 30 cm (Kamermann & Blankenburg 2008, Gaudig *et al.* 2017) to compensate for the low hydraulic conductivity of highly decomposed peat. Because the continuing functionality of the underground irrigation system over time is unclear (Gaudig *et al.* 2017), and considering the high effort required to install it, open ditches with the same spacing as the pipes (5 m) were assumed for large-scale implementation. Costs for their installation by a tracked vehicle equipped with a ditch-digging device, and an excavator to dig ditches along the causeways, were included in the calculation.

The calculation for upscaling Sphagnum farming on cut-over sites assumed mechanical spreading of moss diaspores and straw as demonstrated on bog grassland at Rastede (Table 2), as opposed to manual spreading as in the small field trial on cut-

Table 2. The work steps required to establish *Sphagnum* cultures on bog grassland in Rastede (Lower Saxony, NW Germany).

Site preparation	**Removing the degraded topsoil and providing an even surface** • deciding on the type of production system (Figure 2) • pegging (size) and levelling (depth) of future production strips • transporting the excavator to the field site • taking off sod and the layer of topsoil (30–50 cm, laser-controlled) that is mineralised, limed and enriched with nutrients using a tracked excavator, creating an even surface on the production strips to ensure a homogeneous supply of water to all sub-fields
	Installing infrastructure for water management • excavating narrow ditches (approximately 50 cm wide, 50 cm deep) • constructing outflows for surplus water • installing pumps and underground pipes for irrigation • installing underground cables, sensors and a container for the control centre
	Constructing causeways as management and harvesting infrastructure • using the removed topsoil to build bunds and shaping the bunds as causeways
Initiating *Sphagnum* culture	**Purchase and storage of seeding material** • purchase and storage of *Sphagnum* biomass → diaspores • purchase and storage of straw → mulching
	Spreading *Sphagnum* fragments and straw mulch • transporting machinery, moss and straw to the field • loading the manure spreader, mounted on a snow groomer, with an excavator grab • spreading the moss and straw mulch → establishing the production strips
	Rewetting • initial filling of the ditches • adjusting outflows, refitting non-return valves → raising the water table immediately to minimise desiccation of diaspores

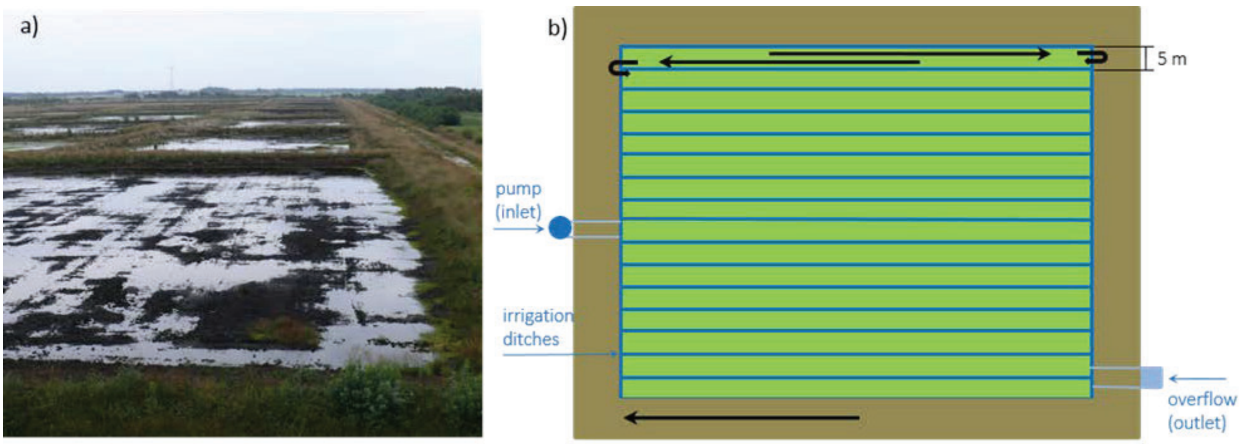

Figure 3. a) Cut-over bog divided into polders, as is commonly done in Germany for restoration purposes; b) schematic illustration (plan view) of Production System 1 on cut-over bog (CO-PS 1) with narrow (5 m) production strips (compare Figure 2a).

over bog at Ramsloh. The diaspore application rate at Ramsloh was 7.9 L m^{-2} (~10 m^3 for 1,260 m^2; Kamermann & Blankenburg 2008, Table 1), and thus similar to that in the Rastede field trial (7.8 L m^{-2}). For comparability, we used the same diaspore price (€750 m^{-3}) instead of calculating the costs of manual collection as actually conducted within the project on cut-over bog. The fictional production site (CO-PS 1) assumed for the cost estimates extends to ~3 ha with 16 moss strips of 5 m × 250 m, *i.e.* it has a net production area of 20,000 m^2 (Figure 3b).

Cultures on floating mats

Two mat components were developed and field tested at large scale, namely: (a) floatable mats; and (b) pre-fabricated mats with *Sphagnum* fragments stitched onto a carrying material and rolled out on the floating mats, either directly after manufacture or after a period of pre-cultivation under sheltered conditions (Figure 4). Costs have been calculated for both of these production options.

For the floating mats, panels of polystyrene foam (2 cm thick) were used as floats to ensure permanent buoyancy. The cost calculations considered panels made of extruded polystyrene foam (XPS) (brand name *e.g.* Styrofoam), which require a higher initial investment but exhibited longer durability in wet environments than expanded polystyrene (EPS) (brand name *e.g.* Styropor). The panels were wrapped in an absorbent textile, *i.e.* recycled polypropylene (PP) fleece (Figure 4a), which ensured the supply of water to the mosses. The fleece connected the single XPS panels together to form a mat of width 1.20 m and length ~13 m, leaving a small gap after every second panel so that the long mat could be folded up for transport from the production plant to the field.

The field-tested *Sphagnum* mats consisted of recycled PP fleece, the *Sphagnum* diaspores (3–4 L m^{-2}), and a thin straw mat covering to reduce evaporation and to fix the mosses. The cost of the straw mats (chopped cereal straw between PP nets, €0.30 m^{-2}) was not included in the calculations because the field trials revealed some disadvantages. During pre-cultivation, the straw mats led to increased weed (*e.g.* cereal) occurrence and had to be lifted regularly because the moss grew through them. On floating mats without pre-cultivation, the straw mats led to conditions becoming too wet for the sensitive phase of moss lawn establishment. Finally, instead of decomposing in the field, the PP net only disintegrated leaving residues in the harvested biomass. For pre-cultivation, the straw mat was replaced with a thin, reusable shading fleece (€0.25 m^{-2}) that improved *Sphagnum* growth by ensuring a moist microclimate. For transport, the cost calculations assumed a separating layer of thin paper in place of the straw mat, to prevent moss fragments from sticking to the bottom side of the rolled-up *Sphagnum* mat.

For soil-based pre-cultivation (Figure 4b), the *Sphagnum* mats were rolled out on ground that had been covered with woven fabric and a thin (0.1 mm) polyethylene film. The moss was protected from direct sunlight by a tunnel covered with shading fabric that was rolled up temporarily for conditioning. An additional shading fleece reduced

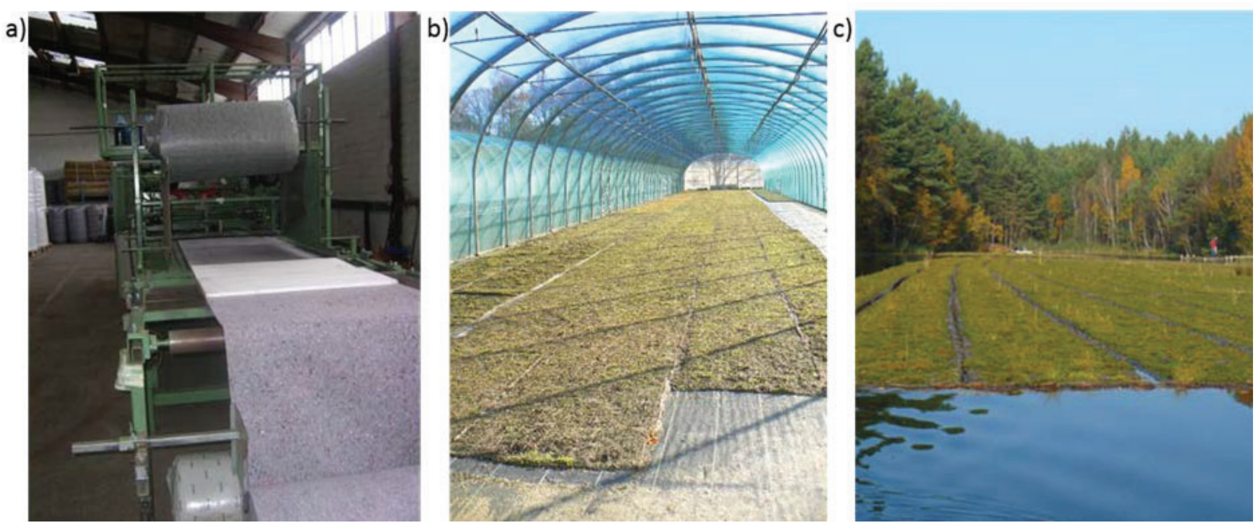

Figure 4. a) Stitching machine for mat production; b) pre-cultivation of *Sphagnum* mats in a shading tunnel (photo: C. Schade, NIRA); c) production site established on a flooded opencast lignite mine.

evaporation. Natural precipitation was supplemented by artificial irrigation to ensure a sufficient water supply. In addition to manual weeding, the application of herbicides and fungicides was successfully tested. Pre-cultivation took 6–12 weeks, meaning that two or three runs can be realised within the annual vegetation period.

Long-distance transport of the mats from the production sites in NW Germany to the large-scale trials on artificial water bodies south of Berlin was by lorry. After unloading, transport to the shore and watering, a motorboat was assumed to pull, place and anchor the floating mats on the water body. The *Sphagnum* mats were rolled out on the floating mats and the single mat strips were reversibly connected to a larger production unit such that they could later be separated for harvesting (Figure 4c). To maintain good vitality of the *Sphagnum* diaspores, all work steps (including delivery and installation) must be carried out without delay.

Establishment costs

Cultures on bog grassland

Preparation of 3 ha of grassland for Sphagnum farming according to Production System 1 (GL-PS 1, 0.81 ha net production area) and Production System 2 (GL-PS 2, 0.87 ha net production area) took 50 working days. The main effort went into taking off and relocating the topsoil (Figure 5). This work step was more time-consuming for GL-PS 1 than for GL-PS 2. In contrast, GL-PS 2 required higher labour and machinery costs for constructing ditches, passages and causeways (Table 3).

Of the total establishment costs of €12.67 and €12.80 m^{-2} (Table 3), site preparation accounted for a minor fraction (GL-PS 1: 11 %, GL-PS 2: 12 %, Figure 6a). The most important cost element was the purchase of *Sphagnum* diaspores (46 %), whereas the seeding work (mainly labour and machinery) accounted for only 7 %. The investment costs for the automatic water management system amounted to 35 % of total cost. Major elements, totalling up to ~€75,000 (Table 3), were site or research specific; for example, the work required to connect the field site to the national power grid (including horizontal drillings), and the material and programming costs for the electronic water management control system. These costs were initially allocated to a relatively small area of ~2 ha. Enlarging the production area to 5.6 ha (in 2016) considerably reduced the proportionate initial cost of irrigation infrastructure *per* unit area (Figure 6a), further emphasising the influence of diaspore costs (46 % → 53 %).

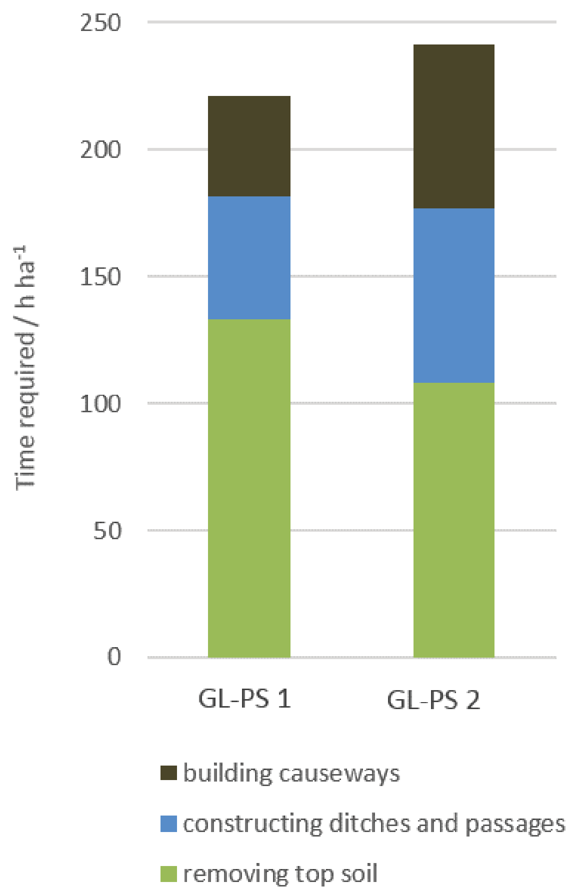

Figure 5. Time required to prepare the site for the pilot trial on former bog grassland, projected for a total area of one hectare to compare Production Systems 1 and 2 (Figure 2), with working steps distinguished.

Cultures on cut-over bogs

The purchase of *Sphagnum* diaspores accounted for 71 % of the total establishment cost of €8.35 m^{-2} (Table 4). Site preparation (7 %) and seeding work (10 %) were of only minor importance (Figure 6b). The investment cost for providing irrigation by wind and mobile pumps amounted to 12 % of the total cost.

Cultures on floating mats

The total investment cost for water-based Sphagnum farming amounted to €17.34 m^{-2}, increasing to €21.43 m^{-2} when pre-cultivation was included (Table 5). The *Sphagnum* diaspores (€750 m^{-3}) accounted for shares of 17 % and 14 %, respectively. The purchase of floating mats and *Sphagnum* mats incurred the highest costs (54 % and 63 % without diaspores), including surcharges added by upstream suppliers to cover their general costs and production risks (12 % and 15 %).

Table 3. Labour, machinery and investment costs of establishing *Sphagnum* cultures on bog grassland in Rastede (Lower Saxony, Germany) in 2011. In order to calculate proportionate costs, some cost items (*) had to be related only to GL-PS 1 and GL-PS 2 (total: ~ 1.68 ha), while others (**) applied to the whole pilot area (2.03 ha net production area).

		Total		**GL-PS 1**	**GL-PS 2**	
Net production area (ha)		1.68 / 2.03		0.815	0.868	
Site preparation						
Transport of the excavator	€	1488	**	598	637	*1*
Pegging and levelling	€	408	*	197	210	*2*
Labour	€	9039	*	4221	4957	*3*
Excavator	€	13,302	*	6133	7169	*4*
Water outlets	€	358	*	346	471	*5*
Total	€	24,594		11,507	13,364	
Proportionate costs per *partial area*	*€ m⁻²*	*1.46*		*1.41*	*1.55*	
Automatic water management						
Pump	€	4353	**	1750	1864	*6*
Electric water meter	€	1560	**	627	668	*7*
Valves	€	3540	*	885	885	*8*
Well shafts	€	1200	**	482	514	*9*
Polyethylene (PE) pipes	€	2266	**	911	970	*10*
Telephone and electricity cable	€	3749	**	1507	1606	*11*
Control and connection cable	€	3050	**	1226	1306	*12*
Installation of underground cables, closing gap to power grid	€	40,302	**	16,202	17,260	*13*
Connection for power supply	€	1510	**	607	647	*14*
Container	€	3800	**	1528	1627	*15*
Control cabinet	€	18,850	**	7578	8073	*16*
Labour (supporting work)	€	8901	**	3578	3812	*17*
Total	€	93,081		36,931	35,151	
Proportionate costs per *partial area*	*$€\ m^{-2}$*	*4.59*		*4.53*	*4.52*	
Seeding work						
Sphagnum diaspores	€	98,388	*	47,639	50,749	*18*
Straw	€	500	**	201	214	*19*
Loading, storage and chopping	€	2726	**	1096	1168	*20*
Transport to the field, loading, supporting works	€	9705	*	4699	5006	*21*
Spreading with adapted snow-groomer	€	3034	**	1220	1299	*22*
Total	€	114,352		54,854	58,436	
Proportionate costs per *partial area*	*$€\ m^{-2}$*	*6.73*		*6.73*	*6.73*	
Proportionate costs per *partial area (without* Sphagnum *diaspores)*	*$€\ m^{-2}$*	*0.89*		*0.89*	*0.89*	
Overall establishment costs	***$€\ m^{-2}$***	***12.79***		***12.67***	***12.80***	
Overall establishment costs (without moss)	***$€\ m^{-2}$***	***6.94***		***6.82***	***6.95***	

KEY TO TABLE 3

1: permits for road transport (oversize), forwarder costs, transport escort
2: labour, digital level (Trimble)
3: mainly operating the excavator (€23 h^{-1})
4: operating hours (€37 h^{-1}), including approximately 3600 L of diesel
5: passages, overflows with fixing device and outlets with non-return valves
6: dirty water motor pump (4 kW) with float switch
7: motor valves, €885 *per* piece
8: controlling water inlet
9: well shafts for valves
10: for water transport from pump to inlet: PE pipes (400m), T-piece, connection *etc*.
11: underground cable for telephone (420 m) and electricity (500 m + 100 m)
12: 1500 m, 1000 m, 500 m
13: horizontal drilling, material, labour (external company)
14: power connection by power grid operator
15: container for control centre, storage and shelter, size: 2.99 m x 2.43 m, 2.35 m internal height
16: material (control cabinet, terminal blocks, cables, cable ducts, adapter, *etc*.) and labour (installation and programming)
17: supporting installation works (container, cable, pipes, well shafts, valves *etc*.)
18: purchasing *Sphagnum* diaspores at a price of €750 m^3; amount spread on average: 78 m^3 ha^{-1}
19: 25 large square bales and round bales at €20 each
20: machinery and labour for loading (forklift), storage and chopping with a field chopper (contracting firm)
21: transport of diaspores/straw to the field (tractors with trailers), excavator for loading snow groomer, operators, supporting works
22: transport of snow groomer (forwarder), adaptation work (mounting manure spreader), seeding work (machine and operator)

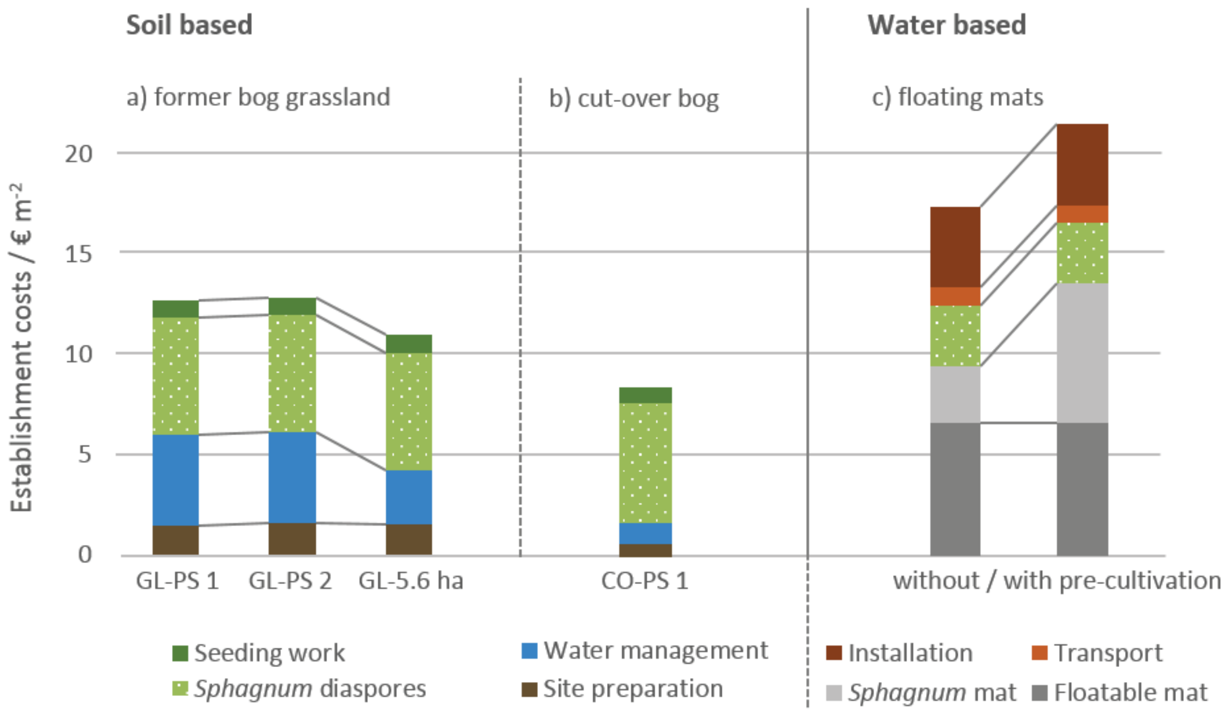

Figure 6. Establishment costs *per* net production area (€ m^{-2}), from left to right: a) on bog grassland for GL-PS 1, GL-PS 2, and with proportionate investment costs for automatic water management reduced by considering the area enlargement from 2 ha to 5.6 ha moss production in 2016 (third column); b) on cut-over bog for a fictional site CO-PS 1 with assumed water supply by wind pump and mobile pump; c) on floating mats without (left column) and with (right column) pre-cultivation of *Sphagnum* mats.

Table 4. Labour, machinery and investment costs of establishing *Sphagnum* cultures on a cut-over bog after milled peat extraction, at a fictional site (CO-PS 1) in Lower Saxony, Germany.

		CO-PS 1	
Net production area (m^2)		20,000	
Site preparation			
Pegging and levelling	€	1500	*1*
Smoothing and poldering	€	3840	*2*
Shaping and compacting causeways	€	2880	*3*
Irrigation ditches along the causeways	€	1360	*4*
Irrigation ditches in the field	€	2550	*5*
Water outlet	€	350	*6*
Total	€	12,480	
Proportionate costs per *partial area*	*€ m^{-2}*	*0.62*	
Water management			
Wind pump (basic supply)	€	15,000	*7*
Mobile pump (demand peaks)	€	5000	*8*
Total	€	20,000	
Proportionate costs per *partial area*	*€ m^{-2}*	*1.00*	
Seeding work			
Sphagnum diaspores	€	118,500	*9*
Straw	€	500	*10*
Loading, storage and chopping	€	2726	*10*
Transport to the field, loading, supporting work	€	9705	*10*
Spreading with adapted snow-groomer	€	3034	*10*
Total	€	134,465	
Proportionate costs per *partial area*	*€ m^{-2}*	*6.72*	
Overall establishment costs	***€ m^{-2}***	***8.35***	
Overall establishment costs (without moss)	***€ m^{-2}***	***2.42***	

KEY TO TABLE 4

1: analysing peat layer depth and profile of mineral subsoil for planning compartment as in the case of restoration
2: 48h, tracked vehicle with operator (€80 h^{-1}), according to experience in restoration work, surcharge of one-third for more careful smoothing
3: excavator with operator (€60 h^{-1}), causeway length: 720 m, required time: approximately 15 m h^{-1} (according to the MOOSGRÜN project)
4: excavator with operator (€60 h^{-1}), ditches: 680 m, required time: approximately 30 m h^{-1} (according to the MOOSGRÜN project)
5: tracked vehicle with ditch-digging device (€85 h^{-1}), ditches: approximately 3,750 m, required time: approximately 125m h^{-1}
6: one outlet (overflows with fixing device according to the MOOSGRÜN project)
7: wind pump, including installation work, for a basic water supply of 10 m^3 ha^{-1} d^{-1}
8: mobile pump + emergency power unit, to meet demand peaks of 100 m^3 ha^{-1} d^{-1}
9: quantity of *Sphagnum* diaspores: 79 m^3 ha^{-1} as in the TORFMOOS project; purchasing price: €750 m^{-3} according to the MOOSGRÜN project
10: according to the MOOSGRÜN project

Table 5. Material, production and installation costs *per* square metre of water-based Sphagnum farming site.

Production of floatable mats			
Panels of extruded polystyrene (XPS), 2 cm thick	€ m^{-2}	2.53	*1*
Fleece, recycled polypropylene (PP) 350g m^{-2}	€ m^{-2}	1.80	*2*
Production costs	€ m^{-2}	1.20	*3*
Surcharge (20 %)	€ m^{-2}	1.11	*4*
[1] Purchase of floatable mat	**€ m^{-2}**	**6.64**	
Production of *Sphagnum* mats			
Sphagnum diaspores (4 L m^{-2})	€ m^{-2}	3.00	*5*
PP fleece, 350 g	€ m^{-2}	0.85	*6*
Production costs	€ m^{-2}	1.00	*3*
Surcharge (20 %)	€ m^{-2}	0.97	*4*
[2] Purchase of *Sphagnum* mats	**€ m^{-2}**	**5.82**	
Pre-cultivation			
Purchase of *Sphagnum* mats [2]	€ m^{-2}	5.82	
Transport from mat plant to pre-cultivation enterprise	€ m^{-2}	0.05	*7*
Costs of pre-cultivation	€ m^{-2}	3.00	*8*
Shrinkage/loss (5 %)	€ m^{-2}	0.44	*9*
Surcharge (20 %)	€ m^{-2}	0.60	*10*
[3] Purchase of pre-cultivated *Sphagnum* mats	**€ m^{-2}**	**9.91**	
Transport to the field site			
Transport of floatable mats	€ m^{-2}	0.48	*11*
Transport of *Sphagnum* mats	€ m^{-2}	0.40	*12*
[4] Forwarder costs	**€ m^{-2}**	**0.88**	
Installation on the water body			
Consumables	€ m^{-2}	0.50	*13*
Machinery/boat costs	€ m^{-2}	0.73	*14*
Labour costs	€ m^{-2}	2.77	*15*
[5] Installation costs	**€ m^{-2}**	**4.40**	
Establishment costs, without pre-cultivation [1+2+4+5]	***€ m^{-2}***	***17.34***	
Establishment costs, with pre-cultivation [1+3+4+5]	***€ m^{-2}***	***21.43***	

KEY TO TABLE 5

1: purchase price for 10,000 m^2 (January 2010), material prices fluctuate according to oil prices, XPS panel: 125 cm x 60 cm x 2 cm
2: price: €0.85 m^{-2}, required amount 3.33 m^2 (double ply, seam allowance, gap to allow folding) *per* mat unit (1.2 m x 1.31 m)
3: labour and machinery costs (stitching, packing, loading), consumables (stitching thread)
4: surcharge on material costs (for purchase, unloading, storage) and on production costs (risks)
5: no established market for *Sphagnum* of regional origin, purchasing costs in projects: €750 m^{-3} → €0.75 L^{-1}
6: high-quality fleece, comparable with new material
7: company owned lorry (one way = 25 km), loading
8: including labour, machinery, investment, and incidental costs for site preparation, establishment, management, harvest, loading
9: surcharge (5 %) on material and production costs for loss of parts not suitable for sale
10: surcharge (20 %) on production costs
11: €600 *per* lorry (about 500 km), assuming 20 pallets with piles of four folded mats, loading height: 2.20 m, 1,250 m^2 of mats
12: €600 *per* lorry (about 500 km), 1,500 m^2 of rolled-up mats
13: assuming costs of €5000 ha^{-1} for anchoring, fixing, tying together, protecting measures
14: wheel loader with pallet handler for unloading and transport to the shore, motorboats for water-based installation work
15: €26 h^{-1}, 4 workers, 5 days of 8 hours is assumed to be required for installing 1500 m^2

Comparing establishment costs

Establishing *Sphagnum* cultures on water bodies (€17.34 / €21.43 m^{-2}, Table 5) was clearly the most expensive procedure when compared to establishment on bog grassland (€12.67 / €12.80 m^{-2}, Table 3) and cut-over bog (€8.35 m^{-2}, Table 4) (Figure 6). Sphagnum farming is generally characterised by high investment costs, but establishes a permanent culture allowing repeated harvests. If the initial establishment costs (Tables 3–5, Figure 6) are converted to annuities, *i.e.* constant annual payments spread over the whole lifetime, the results range from €5,600 ha^{-1} a^{-1} (cut-over bog, 20 years, interest rate 3 %) to €49,500 ha^{-1} a^{-1} (floating mats with pre-cultivation, 5 years, interest rate 5 %). The total cultivation time strongly influences the annual costs whereas altering the interest rate has limited effect (Figure 7).

For the soil-based cultures, 20 years appears to be a reasonable lifetime for investment decisions. *Sphagnum* is known to regenerate better than vascular plants, but we lack experience of long-term regeneration potential and whether harvesting could continue after 20 years. For floating mats, a limitation on the lifetime of materials has to be assumed, resulting in a total cultivation time of nine or ten years depending on the length of one rotation (Table 6).

To relate costs to yields, "best guestimates" of productivity and rotation length (Table 6) were derived from the pilot trials (Table 1). For soil-based cultures, two-thirds of the peatmoss productivity is harvested and one-third is left on the field for regeneration. Since we have no experience of regrowth after harvest for water-based cultures, we calculated intermediate costs for re-establishing *Sphagnum* mats to start a new rotation. Converting the establishment costs into annuities and relating them to the predicted harvestable amount of dry (bio)mass (DM) for the different *Sphagnum* cultures results in proportionate costs of €1,723 t^{-1} DM and €2,646 t^{-1} DM for soil-based, and €9,625 t^{-1} DM and €11,833 t^{-1} DM for water-based Sphagnum farming (Table 6).

Potential production area in Germany

Degraded bogs

Covering about 235,000 ha, Lower Saxony hosts around 70 % of Germany's remaining bog sites (Jensen *et al.* 2012). About 30,000 ha of bog was allocated to peat extraction for growing media production with permits phasing out by 2050 (NLWKN 2006). In 2011, poldering for restoration had begun on an area of ~15,000 ha, to be

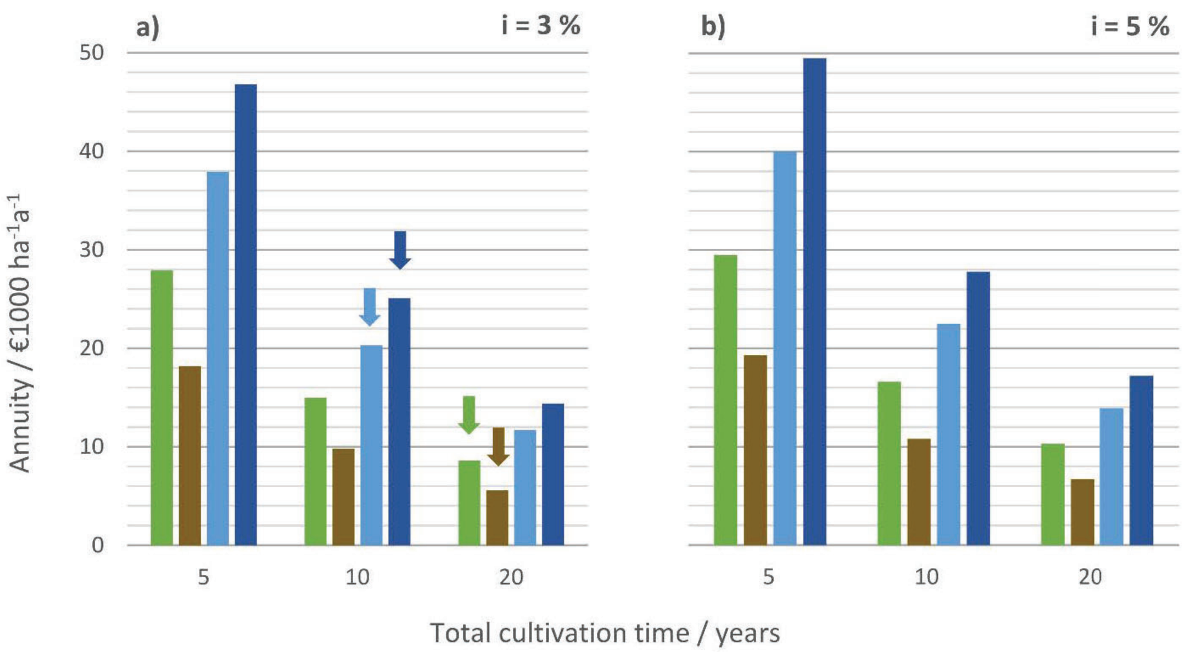

Figure 7. Annuities of initial establishment costs, calculated for an interest rate of a) 3 % and b) 5 %, for Sphagnum farming on former bog grassland (green), cut-over bog (brown) and floating mats without (light blue) and with (dark blue) pre-cultivation, and for assumed total cultivation times of 5, 10 and 20 years. The arrows indicate reasonable cultivation times for the different site types that have been used for further calculations.

Table 6. Relation of the establishment costs to the harvested dry mass (DM) yield.

Sphagnum farming on:	Total cultivation time years	Annuity of establishment costs (i=3%) € ha^{-1} a^{-1}	Rotation length years	Harvested DM yield t ha^{-1}	Average annual DM harvest t ha^{-1} a^{-1}	Proportionate establishment costs € t^{-1} DM
Former bog grassland	20	8,600	4	13	3.25	2,646
Cut-over bog	20	5,600	4	13	3.25	1,723
Floating mats - without pre-cultivation	9	38,500*	3	12	4	9,625
- with pre-cultivation	10	71,000*	2	12	6	11,833

* In addition to initial establishment costs, intermediate costs of re-establishing *Sphagnum* mats after harvest are included.

supplemented with another 12,500 ha by 2040 (Schmatzler 2012). Extraction sites with ongoing peat cutting and an intended agricultural after-use—which could encompass Sphagnum farming on cut-over bog—cover about 500 ha (~5 %) of the total area with extraction permits (pers. comm. 2013, engineering consultancy Hofer & Pautz GbR).

The large majority (around 60 %) of bog sites in Lower Saxony have been drained for agriculture or forestry (Jensen *et al.* 2012). Grassland has been converted to arable land (maize production) and peat extraction sites during recent decades, but remains the dominant land use on bogs encompassing around 90,000 ha (MU 2016).

Acidic water bodies

Acidic artificial water bodies result from peat, sand and lignite mining. In Germany, lakes originating in particular from opencast lignite mines cover a large area. There are about 500 lakes, of which more than 100 are larger than 50 ha (Nixdorf *et al*. 2000). Whereas about half of these lakes have neutral conditions, acidic water bodies occur especially in mining regions with Tertiary geology such as Lusatia in Eastern Germany. The total area of East German mining lakes is around 42,000 ha (Rümmler *et al.* 2003), with lakes over 50 ha accounting for ~36,000 ha (Nixdorf *et al.* 2000). Large lakes are flooded with foreign water, if possible, to increase their utilisation value (Lienhoop & Messner 2009); acidification by groundwater especially affects smaller lakes (Rümmler *et al.* 2004). Thus, most lakes are unsuitable for Sphagnum farming for various reasons including: pH too low; EC too high; pH too high after flooding with basic river water or liming; in use for watersports and recreation; or prioritised for natural development. Accordingly only a quarter, at maximum, of the total lake area seems appropriate, *i.e*. around 10,000 ha.

DISCUSSION

Quality of the data

Canadian experience of restoring cut-over bogs by transferring and mechanical spreading of "moss layer" and straw mulch (Quinty & Rochefort 2003, Landry & Rochefort 2009) stimulated the German trials on Sphagnum farming. By managing the water table to maximise productivity, and by testing new site types such as former bog grassland and floating mats, novel expertise on how to successfully cultivate *Sphagnum* for commercial purposes has been acquired. Further implementation will allow these procedures to be optimised.

For the first comprehensive cost assessments, the availability of real-life data and, thus, data quality differed for the three types of Sphagnum farming sites examined. Real figures (for the field trial on bog grassland, floatable mat production and pre-cultivation) had to be supplemented with estimates when data were missing (field installation of floatable mats on the water) or when the implementation was manual rather than mechanical (on cut-over bog). Because there is, as yet, little or no experience of management, harvesting and long-term cultures, we focused on comparing the establishment costs.

Sphagnum diaspores

The purchase of *Sphagnum* diaspores was the biggest cost factor for establishing soil-based cultures (bog grassland: 46 %, cut-over bog: 71 %;

Figure 6a, b). For floating mats, diaspore costs were relatively less important (14 % and 17 %, Figure 6c). Although the diaspore application rate on bog sites (7.8 and 7.9 L m^{-2}; Table 3, Table 4) was double that for floating mats (4 L m^{-2}; Table 5), overall costs were considerably lower for soil-based than for water-based cultures (Figure 6).

So far, there is no market for living *Sphagnum* of regional provenance in Germany. Due to the lack of supply of *Sphagnum* diaspores in the necessary quantities, the supplier holds a monopoly position. Nevertheless, the price of €750 m^{-3} is assumed to represent the real provision costs since the mosses were collected and sorted manually to provide *Sphagnum* diaspores with a minimal fraction of vascular plants. An important factor of uncertainty results from giving the amount in m^3 since, depending on compaction, varying numbers of diaspores were delivered within the same volume. In the future, mechanical harvesting of *Sphagnum* on cultivation sites or *in vitro* production (Beike *et al.* 2015) is likely to increase diaspore availability and reduce the costs. Reduced diaspore costs will especially benefit soil-based Sphagnum farming.

Soil-based cultivation

Water management

The investment costs for infrastructure to provide precise water management was the second most important cost element. The two variants tested on cut-over bog and former bog grassland illustrated a wide range of possible costs ranging from around €20,000 for a wind pump supplemented by a mobile pump (€1.00 m^{-2}, Table 4) to €93,000 for the installation of a power supply and electronically controlled automatic water management system (€4.59 m^{-2}, Table 3). This large difference is caused solely by the choice of irrigation system and is independent of the previous land use. Alternatively, an electric pump powered by a wind turbine and/or solar panels could be used. Especially when investment costs are high, proportionate costs are reduced considerably when the infrastructure is used for a larger moss production area (Figure 6a, right). Identifying cost-effective, site-specific and reliable solutions for water management is a major challenge for commercial soil-based Sphagnum farming.

Site preparation: cut-over bog versus *former grassland*

Site preparation on cut-over bog (CO-PS 1: €0.62 m^{-2}, Table 4) incurred less than half the costs of site preparation on former bog grassland (GL-PS 1: €1.41 m^{-2}, Table 3), but played a minor role in the overall costs (7 % and 11 %, Figures 6b, 6a). This cost difference arises (a) because smoothing a cut-over site requires less effort than removing the topsoil from former bog grassland, (b) because a tracked vehicle with a wide blade is more efficient than an excavator, and (c) by scale effects (fictional CO-PS 1: 2 ha, GL-PS 1: 0.8 ha).

Site preparation: PS 1 versus *PS 2*

In planning the field trial on bog grassland, we aimed to compare two production systems (Figures 2a, 2c). Due to the limited size (3 ha) and triangular shape of the pilot site, the effort of preparation work (Figure 5) differed only moderately between the two systems. The proportionate cost of site preparation was 10 % higher for GL-PS 2 (€1.55 m^{-2}) than for GL-PS 1 (€1.41 m^{-2}) (Table 3). The share of the net moss production was 50 % for the field trial on former bog grassland. In the case of the fictional site on cut-over bog (CO-PS 1, 3 ha), the share was 68 % (Figure 6b). In PS 1 the area lost for infrastructure might be further reduced by enlarging the compartments.

When implementing PS 1 on former bog grassland at larger scale, more degraded topsoil accrues than is needed for constructing causeways. Therefore, it will be necessary to remove some topsoil from the site to maximise the moss production area. This objective is constrained by the high cost of transport and disposal if no sensible use for the removed peat can be identified. Using the mineralised top layer for causeways and—if further soil removal to compensate height differences is unavoidable—selecting less-decomposed peat layers for growing media production can be considered. In order to cut the costs of site preparation and to mitigate greenhouse gas emissions, topsoil removal must be reduced or avoided by developing alternative approaches for establishing *Sphagnum* directly on former grassland. It is inadvisable to establish PS 2 on cut-over bogs because the peat needed for causeway construction must be excluded from extraction—thus creating opportunity costs (income foregone)—but will nevertheless oxidise, releasing carbon dioxide to the atmosphere.

Challenges of upscaling pilots

The main challenge in establishing soil-based *Sphagnum* cultures is to provide an optimal water supply, avoiding drought and flooding which can hamper the establishment and productivity of moss lawn. Investigations on the suitability of potential production sites (*e.g.* water-holding capacity, water conductivity, availability and quality of irrigation water) and careful control of the water table, especially during the sensitive establishment phase, are prerequisites for successful Sphagnum farming.

The Ramsloh pilot trial was successfully established on cut-over bog (Gaudig *et al.* 2014). However, its transferability to conventional cut-over sites has yet to be proved feasible. On the Ramsloh site peat was initially excavated to create a small basin, the remaining peat layer was 160–195 cm thick, and spreading of both *Sphagnum* and straw mulch was conducted manually (Kamermann & Blankenburg 2008, Gaudig *et al*. 2017). Furthermore, the sufficiency of water supplied *via* irrigation ditches at 5 m spacing, as assumed for the cost calculations, has yet to be field tested on highly decomposed peat. If 50 cm of peat must remain beneath the floors of ditches as a seal to prevent vertical water loss, peat cutting must stop earlier to leave a 1 m (instead of a 0.5 m) peat layer, creating opportunity costs for the peat extracting company. Alternatively, the irrigation effort must be increased to compensate for the additional water loss.

Other field trials of Sphagnum farming on cut-over bogs after milled peat harvesting have been conducted in NW Germany by a state-run organisation and a business company, on areas of 2 ha (2002) and 1 ha (2012), respectively. These failed to establish closed *Sphagnum* lawns, most probably due to inadequate water management. Pouliot *et al.* (2015) demonstrated the feasibility of Sphagnum farming in trenches on previously block-cut peatland in Canada, but also stressed the importance of water management optimisation for improving productivity.

Water-based cultivation

Mats causing major costs

Cultivation on water bodies has the advantage of a permanent water supply. The intention is to imitate floating rafts in flooded peat pits and ditches, which are known to support high *Sphagnum* productivity (Money 1994). However, the high production costs of artificial floatable mats was the main factor contributing (54–63 %, Figure 6c) to the highest overall establishment costs for this approach amongst all of the *Sphagnum* culture methods investigated. Furthermore, the durability of cultures on mats is insufficiently understood. If they have to be replaced, disposal costs for the old floating mats must be taken into account. Generally, all work on open water, including not only the installation (Figure 6) but also the management and harvesting of the mats, requires more effort (*e.g.* time and work safety) than soil-based work.

Challenges of upscaling pilots

Water-based cultures are exposed to wind, waves and ice drift which may spill or sever *Sphagnum* biomass or damage the floating mats, especially on larger lakes. Waterfowl using the mats as artificial islands for roosting and nesting caused damage by picking out moss and increasing the supply of plant nutrients. A prerequisite for Sphagnum farming is an appropriate water quality and a water depth of at least 1 m throughout the year. Fluctuating water levels were a challenge on shallowly flooded cut-over bogs. When the water level was low, the roots of vascular plants (*e.g. Juncus effusus*) grew through the mats into the bottoms of the pools, thus anchoring the mats and causing their inundation when the water table subsequently rose again. Therefore, the calculations assumed that cultivation would be on former opencast lignite mines in the ‘Lusatian Lakeland’ and included costs for long-distance transport of the mats (Figure 6c).

Effects on profitability: relating establishment costs to lifetime and revenues

Higher establishment costs do not necessarily reduce profitability because they represent only part of the overall costs, along with management, harvesting and biomass processing. On the other hand, it is still unknown whether or not certain procedures could pay for themselves in terms of higher revenues by increasing either the quantity or the quality of *Sphagnum* biomass produced. For soil-based Sphagnum farming, the cost advantages of PS1 may be outweighed by reduced productivity due to weed mowing machinery compacting the peatmoss. In the case of water-based Sphagnum farming, pre-culture may be the most suitable way to produce high-value diaspores by growing weed-free ‘monocultures’ of the intended *Sphagnum* species (sheltered conditions, opportunity to use herbicides and fungicides).

Converting establishment costs to annuities (Figure 7) illustrates the high importance of the lifetime of *Sphagnum* cultures for profitability assessment. In comparison with the other approaches, water-based Sphagnum farming is very likely to involve a shorter total cultivation time and intermediate costs for re-establishing *Sphagnum* mats, which will reinforce the disadvantage of high initial costs. Relating the costs of initial and repeated establishment to the harvestable amount of biomass (€ t^{-1} DM; Table 6) confirms the outcome of the calculations relating costs to the net production area (€ m^{-2}; Figure 6), and on this basis water-based Sphagnum farming appears to be even less attractive. However, reasonable profitability estimates rely on verification of the values by long-term real-life data on total cultivation time, durability of the floatable mats, rotation length, regeneration potential after harvesting, and productivity development in the case of repeated cutting. Finally, cultivated *Sphagnum* biomass is not yet traded on the open market, and further investigations to convert dry mass yields (t ha^{-1}) into product volumes (m^3) for revenue calculations are indispensable.

Can the potential Sphagnum farming area meet the demand for white peat in Germany?

The total area (~500 ha) of cut-over peatland in Germany that can potentially be used for Sphagnum farming as new agricultural production is negligible. Rewetting and natural development has become the standard after-use procedure and has been implemented on thousands of hectares. However, several arguments may justify permitting Sphagnum farming instead of natural development—at least temporarily—on peat extraction sites that will become worked-out in the future. Firstly, whereas restoration has achieved limited success in previous decades (Rosinski 2012), Sphagnum farming creates surrogate habitats for rare bog species and improves the provision of ecosystem services (Wichmann *et al*. 2012, Beyer & Höper 2015, Muster *et al.* 2015, Gaudig & Krebs 2016). Secondly, compensation for the impacts of peat extraction might be provided more successfully by restoring other peatlands that have been drained but not extracted. Thirdly, cultivating *Sphagnum* allows the production of a renewable high-quality growing media constituent to reduce the industry's dependence on peat. If 50 % of each newly abandoned peat extraction area were to be rewetted for natural development (as is common practice) but arrangements were negotiated to establish Sphagnum farming as a temporary productive land use on the other 50 %, 5,000 ha of cut-over bog with a net production area of 3,500 ha could potentially be made available.

Germany's ~90,000 ha of bog grassland offers the highest theoretical potential for Sphagnum farming in the country. However, the current legal and policy framework hampers large-scale implementation, *e.g.* through regulations to protect permanent grassland as well as *via* subsidies for drainage-based agriculture and the production of 'biofuels'. Sphagnum farming on bog grassland has enormous potential to increase the provision of ecosystem services, mainly by conserving the carbon store (Günther *et al.* 2017). Adaptations of policy and legislation would be crucial, however, in achieving a shift towards such sustainable land use options (Wichmann *et al.* 2012).

An area of ~10,000 ha of acidic water bodies seemed appropriate for Sphagnum farming. The realistically achievable area is less, however, because only part of the lake surface can be covered by floating mats depending on the shape of the shoreline (*e.g.* bays) and the harvesting regime (*e.g.* space for boats between the mats), as well as for limnological reasons such as the inadvisability of both shading the whole water body and preventing natural oxygenation by wave action. Therefore, we assume a potential effective production area of 5,000 ha. The area of flooded cut-over bog that can potentially be dedicated to Sphagnum farming is very limited (see above), but covering water retention basins with floating mats in order to reduce evaporation (Figure 1) is a reasonable option.

The annual demand for white peat from the German peat and growing media industry is approximately 3.5 million cubic metres (Caspers & Schmatzler 2009). To estimate the potential of Sphagnum farming we assume that *Sphagnum* biomass can replace white peat at a volume ratio of 1:1, average *Sphagnum* dry mass productivities of 3.25, 4 or 6 t ha^{-1} a^{-1} (Table 6), and a bulk density of 30 g L^{-1}. On this basis, *Sphagnum* cultivation on 3,500 ha of cut-over peatland could meet around 10 % of the German demand for white peat. Floating mats extending to 5,000 ha could provide 19 % or 29 % of the demand (without or with pre-cultivated *Sphagnum* mats); but note that the calculation ignores any requirement for diaspores to re-establish (rather than regenerate) harvested *Sphagnum* mats. Finally, a net moss production area comprising 35,000 ha of the country's 90,000 ha of bog grassland could produce sufficient *Sphagnum* biomass to completely replace the white peat requirement of the German growing media industry.

CONCLUSIONS

- Bog grassland has the highest theoretical area potential for Sphagnum farming in Germany and establishment costs can be considerably reduced by choosing a cost-efficient irrigation system.
- Cut-over bogs require the least effort for site preparation, but the feasibility of Sphagnum farming on milled peat sites has yet to be proven by a large-scale field test. The current area potential in Germany is limited, since virtually all sites in Germany are assigned to natural development after peat extraction.

- Floatable mats are not suitable as major *Sphagnum* cultivation sites because they incur the highest overall establishment costs and face challenges such as wind, waves, damage by water birds and limited area potential.
- Further implementation offers considerable potential for optimising procedures and reducing the costs of, for example, *Sphagnum* diaspores, water management and site preparation (mainly by minimising topsoil removal on bog grassland).
- Profitability assessments require further field experience and research into management, harvesting, processing, regeneration, rotation length and overall number of rotations.

ACKNOWLEDGEMENTS

We thank the German Federal Ministry of Food, Agriculture and Consumer Protection (BMELV) and the German Federal Ministry of Economy and Technology (BMWi) for funding the research projects; and our project partners for their co-operation. We gratefully acknowledge the support of our practical partners Torfwerk Moorkultur Ramsloh Werner Koch GmbH & Co. KG, Deutsche Torfgesellschaft mbH, mst-Draenbedarf GmbH and Niedersaechsische Rasenkulturen NIRA GmbH & Co. KG in providing and discussing data relating to procedures and costs.

REFERENCES

Barthelmes, A. (2016) The global potential and perspectives for paludiculture. In: Wichtmann, W., Schröder, C. & Joosten, H. (eds.) *Paludiculture - Productive Use of Wet Peatlands: Climate Protection, Biodiversity, Regional Economic Benefits*, Schweizerbart Science Publishers, Stuttgart, 200–203.

Beike, A.K., Spagnuolo, V., Lüth, V., Steinhart, F., Ramos-Gómez, J., Krebs, M., Adamo, P., Rey-Asensio, A.I., Angel Fernández, J., Giordano, S., Decker, E.L. & Reski, R. (2015) Clonal *in vitro* propagation of peat mosses (*Sphagnum* L.) as novel green resources for basic and applied research. *Plant Cell, Tissue and Organ Culture*, 120(3), 1037–1049, doi: 10.1007/s11240-014-0658-2.

Beyer, C. & Höper, H. (2015) Greenhouse gas exchange of rewetted bog peat extraction sites and a *Sphagnum* cultivation site in northwest Germany. *Biogeosciences*, 12, 2101–2117.

Blankenburg, J. (2004) *Praktische Hinweise zur optimalen Wiedervernässung von Torfabbauflächen* (*Guidelines for Optimal Rewetting of Peat Cutting Areas*). Geofakten 14, Niedersächsisches Landesamt für Bodenforschung, Bremen, 11 pp. (in German). Online at: http://www.lbeg.niedersachsen.de/download/882

Blievernicht, A., Irrgang, S., Zander, M. & Ulrichs, C. (2011) Produktion von Torfmoosen (*Sphagnum* sp.) als Torfersatz im Erwerbsgartenbau (Production of peat mosses (*Sphagnum* sp.) as an alternative for peat in professional horticulture). *Gesunde Pflanze*, 4, 125–131 (in German).

Blievernicht, A., Irrgang, S., Zander, M. & Ulrichs, C. (2012) The youngest peat - Sustainable production of *Sphagnum* sp. and its use as growing media in professional horticulture. Extended Abstract No. 247, *Proceedings of the 14th International Peat Congress* (Stockholm, Sweden), International Peat Society, Jyväskylä.

Blievernicht, A., Irrgang, S., Zander, M. & Ulrichs, C. (2013) *Sphagnum* biomass - the next generation of growing media. *Peatlands International*, 1/ 2013, 32–35.

Caspers, G. & Schmatzler, E. (2009) Vorkommen und Verwendung von Torf in Deutschland (Deposits and utilisation of peat in Germany). *Telma*, 39, 75–98 (in German).

Díaz, F., Larraín, J., Zegers, G. & Tapia, C. (2008) Caracterización florística e hidrológica de turberas de la Isla Grande de Chiloé, Chile (Floristic and hydrological characterisation of Chiloé Island peatlands, Chile). *Revista Chilena de Historia Natural*, 81, 455–468 (in Spanish).

Domínguez, E. (2014) *Manual de Buenas Prácticas para el Uso Sostenido del Musgo* Sphagnum magellanicum *en Magallanes, Chile* (*Manual of Good Practices for the Sustainable Use of* Sphagnum magellanicum *in Magallanes, Chile*). Boletín INIA No. 276, Instituto de Investigaciones Agropecuarias, Centro Regional de Investigación Kampenaike (Institute of Agricultural Research (INIA) Bulletin No. 276, Kampenaike Regional Research Centre), Punta Arenas, Chile, 113 pp. (in Spanish). Online at: http://biblioteca.inia.cl/medios/kampenaike/boletines/NR39326.pdf, accessed 03 Feb 2017.

Emmel, M. (2008) Growing ornamental plants in *Sphagnum* biomass. *Acta Horticulturae*, 779, 173–178.

Gaudig, G., Fengler, F., Krebs, M., Prager, A., Schulz, J., Wichmann, S. & Joosten, H. (2014) Sphagnum farming in Germany - a review of progress. *Mires and Peat,* 13(08), 1–11.

Gaudig, G. & Krebs, M. (2016) Nachhaltige Moornutzung trägt zum Artenschutz bei: Torfmooskulturen als Ersatzlebensraum (Sustainable peatland utilisation contributes to species protection: *Sphagnum* cultures as surrogate habitat). *Biologie in unserer Zeit*, 46(4), 251–257, doi: 10.1002/biuz.201610600 (in German).

Gaudig, G., Krebs, M. & Joosten, H. (2017) Sphagnum farming on cut-over bog in NW Germany: Long-term studies on *Sphagnum* growth. *Mires and Peat*, 20, doi: 10.19189/MaP.2016.OMB.238.

Günther, A., Jurasinski, G., Albrecht, K., Gaudig, G., Krebs, M. & Glatzel, S. (2017) Greenhouse gas balance of an establishing *Sphagnum* culture on a former bog grassland in Germany. *Mires and Peat*, 20(02), 1–16, doi: 10.19189/MaP. 2015.OMB.210.

Jensen, R., Landgraf, L., Lenschow, U., Paterak, B., Permien, T., Schiefelbein, U., Sorg, U.M., Thormann, J., Trepel, M., Wälter, T., Wreesmann, H. & Ziebarth, M. (2012) *Eine Vision für Moore in Deutschland: Potentiale und Ziele zum Moor- und Klimaschutz. Gemeinsame Erklärung der Naturschutzbehörden* (*A Vision for Mires in Germany: Potentials and Targets for Peatland and Climate Protection. Joint Statement of the Nature Conservation Authorities*). Landesamt für Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein, Flintbek, 37 pp. (in German).

Joosten, H. (2010) Abschlussbericht Verbundprojekt „Torfmooskultivierung auf schwimmenden Vegetationsträgern für ein nachhaltiges und umweltfreundliches Torfsubstitut im Erwerbsgartenbau - MOOSFARM“, Teilvorhaben „Torfmooskultivierung auf überstauten Hochmoorflächen“ (Final report of the collaborative project “Sphagnum farming on floating mats to produce a sustainable substitute for peat in commercial horticulture - MOOSFARM”, subproject: “Sphagnum farming on flooded cut-over bogs”). Institute of Botany and Landscape Ecology, University of Greifswald, 166 pp. (in German). Online at: http://edok01.tib.uni-hannover.de/edoks/e01fb10/64025084X.pdf, accessed 03 Feb 2017.

Joosten, H., Gaudig, G. & Krebs, M. (2013) Peat-free growing media: *Sphagnum* biomass. *Peatlands International,* 1/2013, 28–31.

Kamermann, D. & Blankenburg, J. (2008) Erfahrungen und Ergebnisse eines Feldversuchs im Projekt „Torfmoos als nachwachsender Rohstoff“ (Experiences and results of a field experiment in the project “Peat moss as a renewable resource”). *Telma*, 38, 121–144 (in German).

Landry, J. & Rochefort, L. (2009) *Experimental Sphagnum Farming Station Shippagan, New-Brunswick: Activity Report 2003–2008*. Peatland Ecology Research Group, Université Laval, Québec, 50 pp. Online at: http://www.gret-perg.ulaval.ca/uploads/tx_centrerecherche/Report_SphFarm_2003_2008_final_04.pdf, accessed 03 Feb 2017.

Lienhoop, N. & Messner, F. (2009) The economic value of allocating water to the post-mining lakes in East Germany. *Water Resources Management*, 23, 965–980.

Money, R.P. (1994) *Restoration of Lowland Raised Bogs Damaged by Peat Extraction - With Particular Emphasis on* Sphagnum *Regeneration*. PhD thesis, University of Sheffield, UK, 221 pp. Online at: http://etheses.whiterose.ac.uk/1860/1/DX197070.pdf, accessed 03 Feb 2017.

MU (2011) Leitfaden zur Zulassung des Abbaus von Bodenschätzen unter besonderer Berücksichtigung naturschutzrechtlicher Anforderungen (Guideline for permitting resource extraction with special consideration of legal requirements for nature conservation). Ministerium für Umwelt und Klimaschutz (MU) (in German). Niedersächsisches Vorschriften-informationssystem (NI-VORIS) Reference 54-22442/1/1, online at: http://www.nds-voris.de/jportal/?quelle=jlink&query=VVND-281000-MU-20110103-SF&psml=bsvorisprod.psml&max=true, accessed 03 Feb 2017.

MU (2016) *Programm Niedersächsische Moorlandschaften: Grundlagen, Ziele, Umsetzung* (*Peatland Landscapes of Lower Saxony Programme: Basis, Targets, Implementation*). Niedersächsisches Ministerium für Umwelt, Energie und Klimaschutz, Hannover, 71 pp. (in German).

Muster, C., Gaudig, G., Krebs, M. & Joosten, H. (2015) Sphagnum farming: the promised land for peat bog species? *Biodiversity and Conservation*, 24(8), 1989–2009.

Nixdorf, B., Hemm, M., Schlundt, A., Kapfer, M. & Krumbeck, H. (2000) Braunkohletagebauseen in Deutschland. Gegenwärtiger Kenntnisstand über wasserwirtschaftliche Belange von Braunkohlentagebaurestlöchern. Abschlussbericht zum F&E Vorhaben. (Post-mining lakes from opencast lignite mining in Germany. Current knowledge about their water management. Final report on R & D project). Report FKZ 29822240, im Auftrag des Umweltbundesamtes,

Brandenburgische Technische Universität, Cottbus, 519 pp. (in German).
NLWKN (2006) 25 Jahre Niedersächsisches Moorschutzprogramm (25 years of the Lower Saxony Peatland Protection Programme) *Informationsdienst Naturschutz Niedersachse* (Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz), 3/2006, 151–180 (in German).
Oberpaur, C., Puebla, V., Vaccarezza, F. & Arévalo, M.E. (2010) Preliminary substrate mixtures including peat moss (*Sphagnum magellanicum*) for vegetable crop nurseries. *Ciencia Investigación Agraria*, 37, 123–132.
Pouliot, R., Hugron, S. & Rochefort, L. (2015) Sphagnum farming: A long-term study on producing peat moss biomass sustainably. *Ecological Engineering,* 74, 135–147, doi: 10.1016/j.ecoleng.2014.10.007.
Quinty, F. & Rochefort, L. (2003) *Peatland Restoration Guide, Second Edition*. Canadian Sphagnum Peat Moss Association & New Brunswick Department of Natural Resources and Energy, 106 pp. Online at: http://www.gret-perg.ulaval.ca/uploads/tx_centrerecherche/Peatland_Restoration_guide_2ndEd_01.pdf
Reinikainen, O., Korpi, J., Tahvonen, R., Näkkilä, J., Silvan, N. & Silvan, K. (2012) Harvesting of *Sphagnum* biomass and its use as a growing medium constituent. Extended Abstract No. 137, *Proceedings of the 14th International Peat Congress* (Stockholm, Sweden), International Peat Society, Jyväskylä.
Rosinski, E. (2012) Renaturierungspotential von industriell abgetorften Hochmoorflächen in NW-Deutschland (Renaturalisation potential of industrially excavated bog sites in NW Germany). Master thesis, University of Münster, 75 pp. (in German).
Rümmler, F., Füllner, G., Mencke, J. & Jurrmann, S. (2003) Die fischereiliche Nutzung von Braunkohletagebaurestseen (Fishery in post-mining lakes formed by opencast lignite mining). *Fischereiliche Nutzung von Bergbaurestseen, Schriftenreihe der Sächsischen Landesanstalt für Landwirtschaft*, 8(4), 1–12 (in German).
Rümmler, F., Ritterbusch, D., Schiewe, S. & Weichler, F. (2004) Fischereiliche Bewirtschaftung von Braunkohletagebauseen, Möglichkeiten und Besonderheiten (Managing post-mining lakes from opencast lignite mining for fishery - options and particularities). In: Lukowicz, M. & Hilge, V. (eds.) *Fischereiliche Bewirtschaftung künstlich angelegter Gewässer, Arbeiten des deutschen Fischerei-Verbandes e.V. (Fisheries Management of Man-made Water Bodies, Proceedings of the German Fisheries Association*, 80, 29–57 (in German).
Schmatzler, E. (2012) Die Torfindustrie in Niedersachsen - Ergebnisse einer Umfrage zur Zukunft der Torfgewinnung in Niedersachsen (The peat industry in Lower Saxony - results of a survey on the future of peat extraction in Lower Saxony). *Telma*, 42, 27–42 (in German).
von Post, L. (1924) Das genetische System der organogenen Bildungen Schwedens (The genetic system of organogenic deposits in Sweden). In: Comité International de Pédologie, IVème commission (commission pour la nomenclature et la classification des sols, commission pour l'Europe, président: B. Frosterus) (ed.) Mémoires sur la Nomenclature et la Classification des Sols, Helsingfors/ Helsinki, 287–304 (in German).
Wichmann, S., Gaudig, G., Krebs, M. & Joosten, H. (2012) Paludiculture - ecosystem services of Sphagnum farming on rewetted bogs in NW Germany. Extended Abstract No. 369, *Proceedings of the 14th International Peat Congress* (Stockholm, Sweden), International Peat Society, Jyväskylä.
Wichmann, S., Gaudig, G., Krebs, M., Joosten, H., Albrecht, K. & Kumar, S. (2014) *Sphagnum* farming for replacing peat in horticultural substrates. In: Biancalani, R. & Avagyan, A. (eds.) *Towards Climate-Responsible Peatlands Management*, Mitigation of Climate Change in Agriculture Series 9, Food and Agriculture Organization of the United Nations (FAO), Rome, 80–83.
Zegers, G., Larraín, J., Díaz, F. & Armesto, J. (2006) Impacto ecológico y social de la explotación de pomponales y turberas de *Sphagnum* en la Isla Grande de Chiloé (Ecological and social impact of *Sphagnum* pomponales and peat exploitation in the Isla Grande de Chiloé). *Revista Ambiente y Desarrollo,* 22 (1), 28–34 (in Spanish).

Submitted 24 Mar 2016, final revision 18 Apr 2017
Editor: Stephan Glatzel

Author for correspondence:
Sabine Wichmann, Institute of Botany and Landscape Ecology, Ernst Moritz Arndt University of Greifswald, Partner in the Greifswald Mire Centre, Soldmannstraße 15, 17489 Greifswald, Germany.
Tel: +49 3834 420 4143; Fax: +49 3834 420 4107; E-mail: wichmann@uni-greifswald.de

Paper V

Wichmann, S., Krebs, M., Kumar, S., Gaudig, G. (2020)

Paludiculture on former bog grassland:

Profitability of Sphagnum farming in North West Germany.

Mires and Peat, 26 (8): 1–18.

Paludiculture on former bog grassland: Profitability of Sphagnum farming in North West Germany

S. Wichmann[1], M. Krebs[1], S. Kumar[2], G. Gaudig[1]

[1]Institute of Botany and Landscape Ecology, Greifswald University, partner in the Greifswald Mire Centre, Germany
[2]Torfwerk Moorkultur Ramsloh, Saterland, Germany

SUMMARY

Sphagnum farming provides an alternative to detrimental peatland drainage in two ways. Firstly, *Sphagnum* mosses are cultivated on rewetted peatlands. Secondly, *Sphagnum* biomass is a high-quality growing media constituent suitable for replacing peat in horticulture. This study investigated the shift from drained bog grassland to a wet Sphagnum farming site from the micro-economic perspective. Based on five years of field experience, we calculated costs and revenues of Sphagnum farming for a total cultivation time of 20 years. Sensitivity analysis encompassed costs, yields, prices and the effect of public non-market payments. We found that cultivated *Sphagnum* biomass could not compete with peat at current market prices, whereas its use for orchid cultivation was economically viable in the case of medium to high *Sphagnum* productivity. Selling *Sphagnum* shoots as founder or "seeding" material was profitable even in pessimistic scenarios with high costs and low yields. Cost-covering prices for *Sphagnum* biomass substituting peat seem achievable, if end consumers pay a surcharge of 10 % for plants cultivated without using peat (peat free). A commercial-scale implementation, an increasing market demand for renewables, and setting climate targets for the agricultural and horticultural sectors will accelerate the development of Sphagnum farming as a profitable alternative to drainage-based peatland agriculture and peat extraction.

KEY WORDS: break-even price, net present value, peatland agriculture, sustainable growing media

INTRODUCTION

Drainage has commonly been a pre-requisite for the productive use of peatlands, thereby turning unnoticed ecosystem services into major disservices. Nowadays, it is widely acknowledged that draining peatlands for agriculture and peat extraction results in land degradation, soil loss and high greenhouse gas (GHG) emissions; and that sustainable peatland management can be achieved only with high water tables (FAO 2014). The Paris Agreement on limiting global warming to well below 2 °C compared with pre-industrial times (UN 2015) was especially effective in raising general awareness of the ambivalent role of peatlands in contributing to either climate cooling or climate warming. Peatlands are the largest terrestrial organic carbon store, while covering less than 3 % of the global land area (Crump 2017). In contrast to the usually short-term storage of carbon in living biomass, peatlands provide long-term storage for the carbon captured by biomass over hundreds and thousands of years. Drainage turns peatlands into major sources of GHG emissions, releasing CO_2 and N_2O from the aerated peat layer and CH_4 from the drainage ditches (Joosten *et al.* 2016). Drained peatlands cover only 0.4 % of the global land area but are responsible for 5 % of all anthropogenic GHG emissions globally (Joosten 2015). Bringing the water level near to the surface (rewetting) is the most effective measure to preserve the carbon stock, re-initiate a wide range of important ecosystem services and enhance biodiversity (Bonn *et al.* 2016), but usually involves the abandonment of land use.

Paludiculture (*palus*: swamp, *cultura*: cultivation) is agriculture or forestry on wet peatlands and thus offers sustainable land use options for degraded peatlands after rewetting (Wichtmann *et al.* 2016). On rewetted bogs, *Sphagnum* mosses are promising plant species for paludiculture. The cultivation of *Sphagnum* ('Sphagnum farming') produces a renewable growing media constituent that is a suitable substitute for slightly decomposed *Sphagnum* peat ('white peat') in professional horticulture (Gaudig *et al.* 2018). During the last two decades, Sphagnum farming pilot sites have been established on: (a) cut-over bog (Pouliot *et al*. 2015, Gaudig *et al.* 2017, Graf *et al.* 2017), (b) artificial floating mats (Blievernicht *et al.* 2011, 2012) and (c) former bog grassland (see below). Wichmann *et* *al.* (2017) compared the procedures and the costs of establishing commercial *Sphagnum* cultures on these three types of production sites. However, a comprehensive economic evaluation of Sphagnum farming was not possible at that time, due to the lack of field data on management and harvest.

In this article we present the first profitability assessment for Sphagnum farming. Our calculations are based on the first five years of field experience on former bog grassland in North West Germany and anticipate costs and revenues for a total cultivation time of 20 years. While qualitative competitiveness with peat has been shown for *Sphagnum* biomass as a growing media constituent (e.g. Emmel 2008, Oberpaur *et al.* 2010), we examine its current competitiveness in terms of price and discuss market prospects.

METHODS

Study area

The pilot site is located near Rastede in Lower Saxony, North West Germany (53° 15.80' N, 08° 16.05' E). The main land uses in the study area are dairy farming and, to a lesser extent, suckler cow husbandry. Drainage and agricultural use of peatlands has been causing subsidence by compression, shrinkage and oxidation (Eggelsmann 1986). The surface of the peatland 'Hankhauser Moor' now lies up to 1 m below sea level and drainage water has to be pumped out to the North Sea (Hofer & Pautz GbR 2005). The pilot site was used as bog grassland until 2010. Starting up Sphagnum farming involved creating an even surface (for optimal water management), relocating degraded topsoil to create causeways, removing existing drainage pipes and installing infrastructure for water management (e.g. pumps, irrigation ditches and outflows) (see Wichmann *et al.* 2017). The field trial was established in 2011 (Figure 1a) on a 4 ha site with a net area of 2 ha of *Sphagnum* production fields, the remaining area being occupied by infrastructure like causeways and ditches (Wichmann *et al.* 2017). In 2016, the first harvest (Figure 1b) provided *Sphagnum* shoots as founder material for extension of the Sphagnum farming trial to about 14 ha (net: 5.6 ha) (Figure 1c). On the harvested production fields, the lower part of the *Sphagnum* lawn remained to allow *Sphagnum* regrowth and repeated harvests (cf. Krebs *et al.* 2018). Site conditions (e.g. climate, hydrology and nutrients) are described in Brust *et al.* (2018) and Temmink *et al.* (2017).

Cost data and calculation

The considered costs of Sphagnum farming encompass establishment, management, harvest, transport and the processing of *Sphagnum* biomass to create a marketable product. The practical work was conducted by a regional company whose business involves extracting peat and producing growing media for professional horticulture (Torfwerk Moorkultur Ramsloh). We compiled data on labour and machinery use (daily time sheets), standard costing rates (accounting records of the peat company) and payments for materials and contractors (e.g. invoices for irrigation pumps and installation work) covering the period from establishment to first harvest (2011–2016). We assumed regrowth of the residual *Sphagnum* layer after harvesting by cutting (cf. Krebs *et al.* 2018) and used the data from the first rotation period to anticipate costs for a total cultivation time of 20 years including four harvests (Figure 2). Opportunity costs of conventional grassland use were excluded from the calculations because the profit foregone would be highly dependent on European Union (EU) agricultural subsidies, whose continuation for another 20 years cannot be assumed because this would conflict with the EU's climate objectives.

Establishment costs accrue only once at the beginning of the cultivation time ($t = 0$) and include site preparation, investment for water management and spreading of *Sphagnum* shoots as founder material (Figure 1a). The necessary working steps, related costs and a description of the pilot site consisting of *Sphagnum* production fields, irrigation ditches and causeways (Figure 1c) is presented in detail in Wichmann *et al.* (2017). In addition, we investigated the establishment costs for extension of the pilot site in 2016 and incorporated the new cost data for comparison.

The management costs of the Sphagnum farming site are annual costs. They encompass all costs related to water management and site maintenance. Based on five years of experience, we used real life data from the pilot site to calculate plausible values. For example, we chose the most efficient practice of weed mowing on the *Sphagnum* production fields to extrapolate costs instead of calculating real life working hours of trial and error with different mowing equipment. In addition, spreading of additional *Sphagnum* for replenishing gaps in the developing moss carpet in the second year after establishment, as conducted in 2012 (Gaudig *et al.* 2014), was not necessary in 2017 for the extended area and thus was not taken into account as an essential management measure.

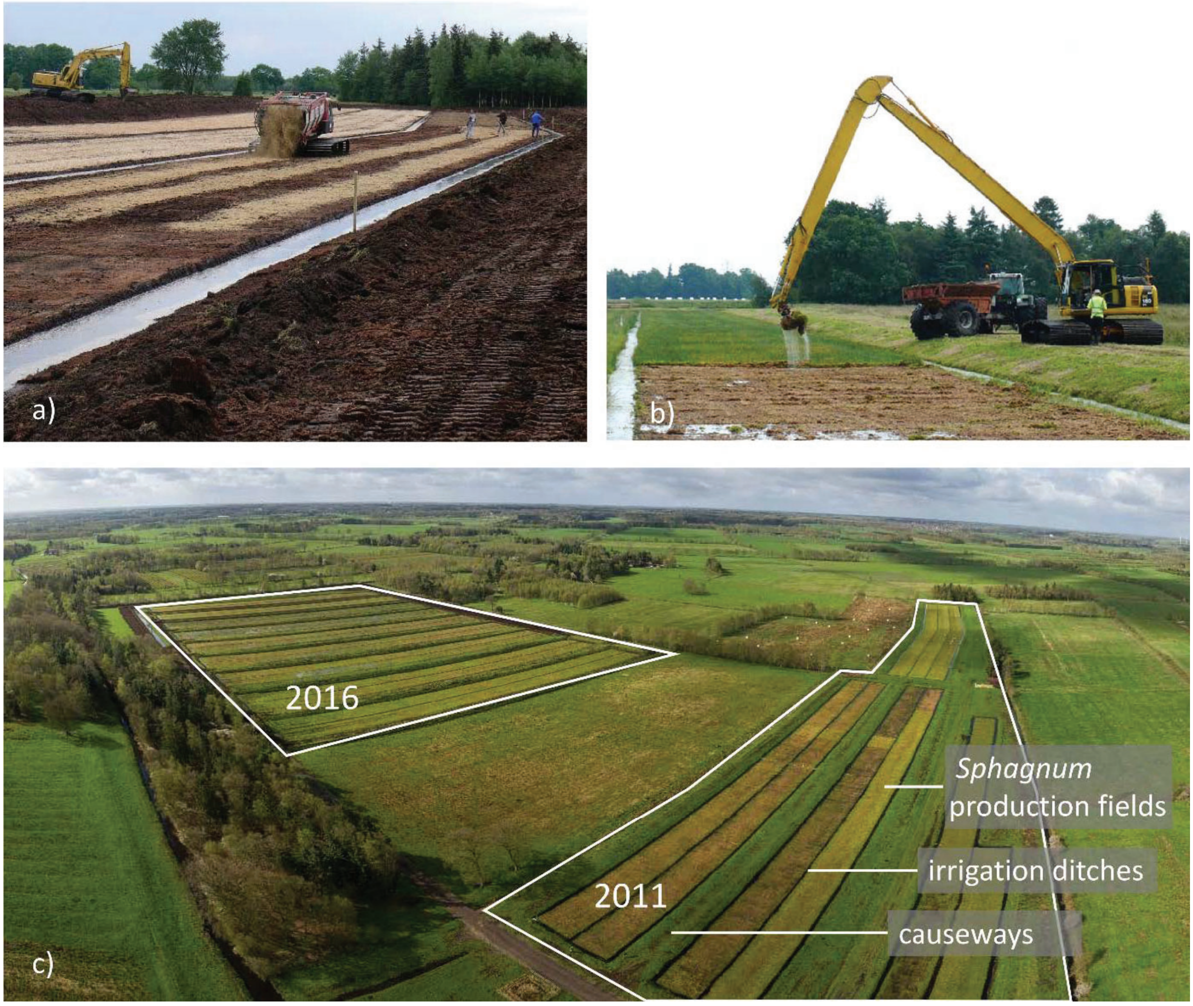

Figure 1. a) Spreading *Sphagnum* shoots with an adapted snow groomer during establishment of the Sphagnum farming pilot. b) First harvest using an excavator with long arm and mowing bucket. c) Aerial view of the pilot site with the five-year-old section established in 2011, the extension section established in 2016 and the surrounding drained grassland. Photos: a) and b) Sabine Wichmann, c) ASEA aerial.

Figure 2. Timeline of the first five years of Sphagnum farming on former bog grassland (dark grey) (Rastede, Lower Saxony) and assumptions for repeated harvests with a rotation length of five years and a total cultivation time of 20 years (light grey).

The first mechanical harvest of the Sphagnum farming site was conducted in June 2016 ($t = 5$). An excavator standing on the causeway was equipped with a long arm and mowing bucket to cut the mosses and load the biomass into a tractor-pulled dumper (Figure 1b) for transport off the site. The mowing bucket and tractor were fitted with GPS trackers (Wintec WBT-202) to log operation times. The transport costs were based on peat handling and include loading of the harvested *Sphagnum* biomass and road transport to the processing plant at a distance of 70 km.

Biomass processing was tested in a commercial plant producing growing media for professional horticulture (Torfwerk Moorkultur Ramsloh), using its standard equipment. The processing steps encompassed drying the harvested biomass in piles in the field or on concrete to a water content of 70–80 %, cleaning in the vapour treatment facility for peat to prevent germination of seeds and sprouting of other plant parts, and separating it into fine and coarse fractions in the screening line usually used for peat (Kumar 2017). The harvest, transport and processing costs were calculated for the years t = 5, 10, 15 and 20 (Figure 2).

Revenue data and calculation

The revenues of Sphagnum farming depend on *Sphagnum* productivity (accumulated biomass in dry mass tons per hectare), the yield (harvested biomass in dry mass tons per hectare), the conversion factor from weight to volume (calculating the yield in m^3 per hectare), the selling price (€ per m^3 according to the application) and non-market payments (€ per ha).

Sphagnum productivity was determined on the pilot site. Before mechanical harvesting, the above-ground biomass accumulated over five years was cut with scissors on 30 plots (randomly distributed over the production fields, cf. Hurlbert 1984, size: 15 × 15 cm). For each plot, *Sphagnum* species, other mosses, vascular plants and litter were separated and dried to constant weight (80 °C for 48 h, Hendry & Grime 1993). Values of the dry mass of *Sphagnum* biomass after five years' growth were used to calculate the average annual productivity. In addition to the mean value, we used the lowest and highest value within the 1.5× interquartile range (IQR) of the lower quartile and upper quartile, respectively, to define three productivity levels.

It was not possible to directly measure the harvested yield. Therefore, we analysed the biomass remaining after harvest on 30 plots (size: 15 × 15 cm) by determining the dry mass of the different biomass components as described above. We compared values of the mean dry *Sphagnum* biomass remaining after mechanical harvest and the mean dry *Sphagnum* biomass grown over five years to determine the fraction of biomass remaining on the land after harvesting. This was subtracted from the biomass productivity (low, mean and high values) to calculate the respective harvested yields. Dry mass yields were converted into volumes (m^3), since volume is the usual trading unit for growing media constituents and substrates. To calculate the conversion factor, the bulk densities of 16 biomass samples of different *Sphagnum* species and origins was determined according to the European standard DIN EN 12580. Considering the water content, we calculated the mean dry mass bulk density and used ± 1 standard deviation as the high and low levels of the conversion factor in the sensitivity analysis (Table 1).

Since *Sphagnum* biomass is used not only as an alternative to peat in growing media but also for applications of higher market value (e.g. for orchid

Table 1. Overview of sensitivity analysis varying input variables for profitability assessment and break-even price calculation. Abbreviations for variables as in the equations, DM = dry mass.

Input variable	Unit	Levels of variation	
Costs (*C*)			
Establishment costs (E_0)	€ ha^{-1}	2	Scenario A: high costs (year: 2011) Scenario B: medium costs (year 2016)
Management costs (M)	€ ha^{-1}	2	Scenario A: high costs (period: 2011–2016) Scenario B: medium costs (reduction by 25 %)
Revenues (*R*)			
Productivity	DM t ha^{-1} yr^{-1}	3	Low / Mean / High
Harvested yield	%	1	Mean
Bulk density (conversion factor)	DM g L^{-1}	2	Low / High
Market price	€ m^{-3}	3	Low / Medium / High
Non-market income	€ ha^{-1}	2	No additional revenues / Medium payment level

cultivation or as founder material for Sphagnum farming sites), we considered three price levels in the profitability calculation. Market revenues are related to harvest and processing and were, therefore, calculated for the years t = 5, 10, 15 and 20. Additionally, the effect of annual public non-market payments on profitability and break-even price was tested (Table 1).

As for the costs, we used the data from the first rotation period to calculate revenues for the following three harvests, assuming constant *Sphagnum* biomass productivity and constant prices over the total cultivation time.

Investment appraisal

Costs and revenues of Sphagnum farming are spread irregularly over the total cultivation time (T) of 20 years. As is common for permanent cultures, Sphagnum farming requires a one-off investment for establishment at the beginning and management costs every year, whereas harvesting costs and market revenues arise every five years. Therefore, we conducted an investment appraisal discounting all cash flows of costs (C) and revenues (R) that occur at a time (t) to a Present Value ($PV, t=0$) (Equation 1, Equation 2). We used a discount rate (r) of 3 % since bank interest rates have been low in Germany for many years. Inflation was excluded from the discount rate (i.e. real discount rate in contrast to nominal discount rate), and from all cash flows which were thus measured in the value of t_0. If the Net Present Value (NPV) (Equation 3) is positive, future revenues can cover the initial investment costs for establishment (E_0) and all further costs related to management (M), harvest (H), transport (S) and processing (P). Transferring the NPV to an Annuity (A) results in a constant annual value spread over the whole lifetime (Equation 4).

$$PV\ (C) = E_0 + \sum_{t=0}^{T} \frac{(M+H+S+P)_t}{(1+r)^t} \qquad [1]$$

$$PV\ (R) = \sum_{t=0}^{T} \frac{R_t}{(1+r)^t} \qquad [2]$$

$$NPV = PV\ (R) - PV\ (C) \qquad [3]$$

$$A = NPV * \frac{(1+r)^T * r}{(1+r)^T - 1} \qquad [4]$$

RESULTS

Establishment costs

Data on establishment costs were collected by installing a Sphagnum farming trial on 4 ha in 2011 and on another 10 ha in 2016 (Figure 1c). The data from 2011 represent a high cost scenario, the data from 2016 represent a medium cost scenario. Major cost determinants were the origin of the founder material (purchase vs. own production) and the size of the area influencing proportionate costs, as well as the time requirement and cost rates for site preparation.

The establishment costs amounted to about € 128,000 per hectare net area of *Sphagnum* production fields in 2011 (Wichmann *et al.* 2017) and to € 98,000 in 2016 (Figure 3). For site preparation, the cost in 2016 was higher than in 2011 (+148 %), for two reasons. First, prices for machinery use increased, e.g. by 54 % for an excavator hour. Secondly, the time required doubled (496 h ha^{-1} vs. 248 h ha^{-1}) because of adverse weather conditions (frost, fog) and because more peat was moved than in 2011 in order to create an even surface despite large depressions. Thus, site preparation was the most important cost item in 2016 (Figure 3). However, the higher costs were outweighed by lower proportional investment in water management, due to a larger irrigated area (2 ha in 2011 vs. 5.6 ha in 2016). Additionally, the cost of *Sphagnum* shoots, which dominated the establishment costs in 2011, was 41 % lower in 2016 because own founder material had been cultivated. Total establishment costs were 23 % lower in 2016 (medium cost scenario) than in 2011 (high cost scenario) (Figure 3). Detailed calculations are included in the Appendix (Table A1).

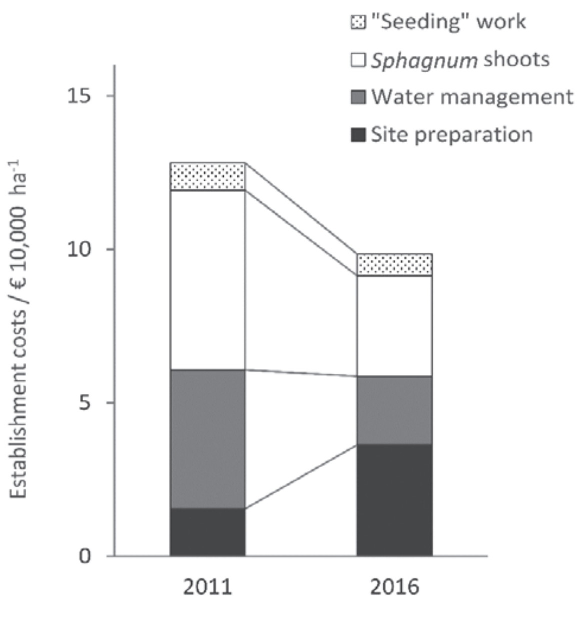

Figure 3. Costs of establishing a Sphagnum farming pilot site on former bog grassland in 2011 (2 ha of *Sphagnum* production fields) (cf. Wichmann *et al.* 2017) and of the extension to 5.6 ha in 2016 (cf. Table A1).

Management costs

During the first rotation period (2011–2016), 73 % of the total management costs were related to site maintenance (Figure 4). The dominating activity was weed control on the *Sphagnum* production fields by regular mowing of vascular plants with a single-axle motor mower (6–8 times per year), followed by cleaning of the irrigation ditches with an excavator and mowing bucket (in 2013 and 2015) and mulching of the causeways with a tractor (4–6 times per year) (Figure 4). Maintenance costs were lower in 2011 (establishment phase) and in the year (2016) ending with harvest in June (see Figure 6b; Table A2).

Harvesting and processing costs

Harvesting an area of 0.58 ha in June 2016 took five days of 9–12 working hours each. The total time of 55 hours included frequent waiting periods because the harvested *Sphagnum* biomass was used directly to enlarge the pilot site and the performance of the "seeding" machine spreading the founder material was the limiting factor. For the labour costs of the two machine operators, we used their actual working hours as a very conservative estimation (55 hours each, i.e. 94 h ha^{-1} per person, € 23 h^{-1}). For the machines, GPS tracking allowed us to determine a realistic performance of 50 h ha^{-1} for harvesting and loading (excavator and tractor) and an additional 12 h ha^{-1} for field transport (tractor, 50–300 m one way). Costs for excavator and tractor operation during harvest in 2016 totalled about € 12,600 ha^{-1}, while transport and processing costs added up to € 7.43 m^{-3} (Table A2).

Yield, bulk density and price levels

For calculating market revenues, we used different levels of three factors: yield arising from low, mean or high productivity, bulk density and price level (Table 1). During five years of cultivation (May 2011 to April 2016), dry mass productivity reached mean values of 24 t ha^{-1} (low: 15 t, high: 34 t) (Figure 5a), i.e. 4.9 t ha^{-1} yr^{-1} (low: 3.1 t, high: 6.8 t). On average, 35 % of the grown-up biomass remained after harvesting in June 2016 (Figure 5a). For the profitability calculation we assumed an average harvested dry mass yield of 16 t ha^{-1} (low: 10 t; high: 22 t), i.e. 3.2 t ha^{-1} yr^{-1} (2.0 t; 4.4 t). For the conversion factor, we chose 20 and 38 g L^{-1} based on the determination of mean dry mass bulk density ± 1 standard deviation (29.0 ± 9.36 g L^{-1}, Figure 5b, cf. Table A3). The market value of *Sphagnum* biomass varies strongly according to the application. It ranges from € 25 m^{-3}, a common price for the slightly decomposed *Sphagnum* peat ('white peat') used in horticultural growing media, through e.g. € 165 m^{-3} for use in the cultivation of orchids, to € 750 m^{-3} for the *Sphagnum* shoots that were used as founder material to populate the pilot site in 2011 (Wichmann *et al.* 2017).

Extrapolation to 20 years: Present Values, Annuities and break-even price

To estimate costs over the total cultivation time of 20 years, we calculated two scenarios which differ in terms of establishment and management costs based on the experience of the field trial.

Cost Scenario A reflects high costs. We used the cost data of the first rotation with establishment in 2011, management and first harvest (Tables A1, A2) to extrapolate corresponding costs to the following rotations. For management we estimated average values of € 5,943 ha^{-1} for the years of harvest (t = 5, 10, 15, 20), reflecting reduced effort due to slow vascular plant regrowth, and € 11,266 ha^{-1} for the other years (Figure 6b). The total *PV (C)* ranged from € 312,000 to € 356,000 ha^{-1} (Figure 7, Table A4) depending on harvested yield and bulk density, which influenced the costs of harvesting, transport and

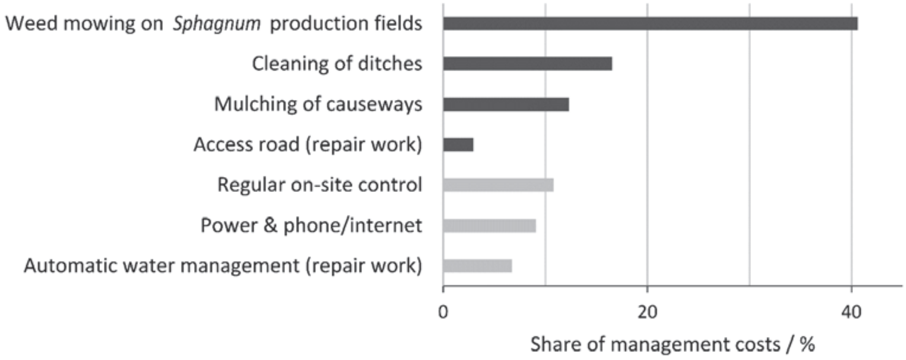

Figure 4. Management costs in 2011–2016 showing the shares of the single cost items for site maintenance (dark grey) and water management (light grey).

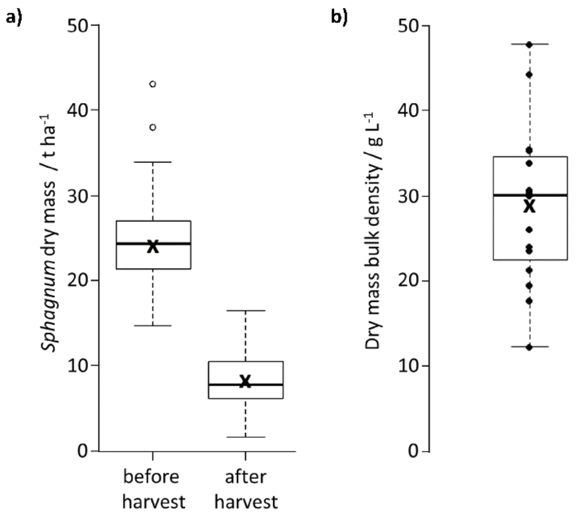

Figure 5. a) *Sphagnum* dry mass after five years of growth, before and remaining after harvest (each $n = 30$); and b) dry bulk density (n = 16, cf. Table A2). The plot shows the median (bold line), the mean (x), the upper and lower quartiles (including 50 % of the data and creating the box), the whiskers representing the lowest and highest values still within 1.5 interquartile range (IQR) of the lower and upper quartile, respectively, and the outliers (o), i.e. the values outside these ranges.

processing. Management costs constituted the largest share (44–50 %) and establishment costs were the second most important (36–41 %) (Figure 6a).

Cost Scenario B reflects medium costs. We used the lower establishment cost value of the year 2016 (Figure 3) and assumed a 25 % reduction in management costs. Consequently, the *PV (C)* reduced to a range of € 243,000 to € 287,000 ha^{-1} (Table A4), which is a saving of € 69,000 ha^{-1} compared to Cost Scenario A.

The Present Value of the revenues (*PV (R)*) ranged very widely, from € 18,000 to € 2,312,000 ha^{-1} (Figure 7, Table A4). The negative *NPV*s (Figure 7) showed that a price of € 25 m^{-3} did not cover the costs of Sphagnum farming. At a price of € 165 m^{-3}, mean or high average dry mass yields (3.2 and 4.4 t ha^{-1} yr^{-1}) were cost-covering when a low bulk density (20 g L^{-1}) was assumed. Selling *Sphagnum* biomass for € 750 m^{-3} resulted in a positive annuity of € 16,200 ha^{-1} yr^{-1} even in case of low yield (2 t ha^{-1} yr^{-1}) and high bulk density (38 g L^{-1}) (Figure 8a), and up to € 131.500 ha^{-1} yr^{-1} at high yield (4.4 t ha^{-1} yr^{-1}) and low bulk density (20 g L^{-1}) (Figure 8c).

In addition to calculating profit or loss with three given price levels, we determined price levels at which production costs were covered. The break-even price ranged from € 115 to € 423 m^{-3} for Cost Scenario A and from € 93 to 330 m^{-3} for Cost

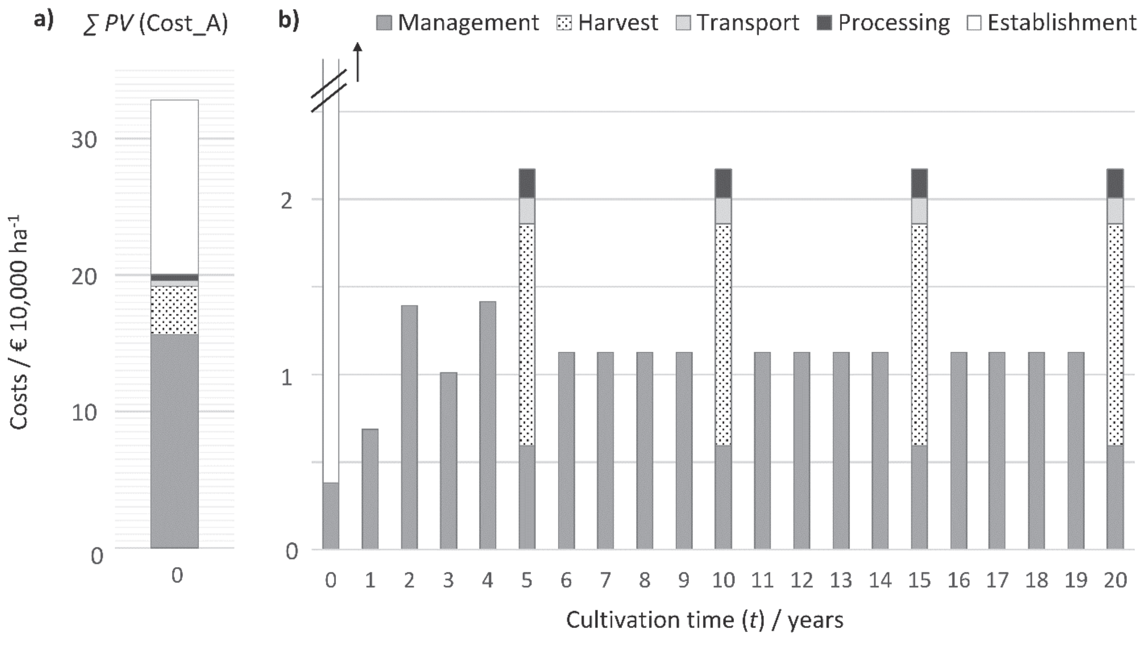

Figure 6. Costs in Scenario A (dry mass average yield: 3.2 t ha^{-1} yr^{-1}, 20 g L^{-1}): a) *PV (C)*, i.e. all costs discounted ($r = 3$ %) and summed for the year of establishment ($t = 0$); b) costs of establishment, management, harvest, transport and processing according to their occurrence during the cultivation time ($t = \text{x}$).

Scenario B (Table 2), equating to a reduction of about 21 % (€ 22–93 m^{-3}, 19–22 %).

In addition to market revenues, EU agriculture is commonly supported by public payments. We assumed a non-market income through agricultural subsidies of € 300 ha^{-1} yr^{-1}, comparable with the average level of current EU direct payments (Pillar I) in Germany (EC 2017). Additionally, we assumed the remuneration of ecosystem services provision at € 1,000 ha^{-1} yr^{-1}. The non-market income reduced the break-even price by about 7 % (€ 6–26 m^{-3}, 5–8 %) (Table 2).

DISCUSSION

Profitability at farm level

Influence of price levels

The pilot site allowed a first cost and profitability assessment for large-scale, mechanically implemented Sphagnum farming based on real-life data. Our data show that *Sphagnum* biomass cultivated on former bog grassland cannot compete with peat at its current market price; but also indicate that, with medium and high yields at low bulk density, profitability is achieved if the *Sphagnum* is

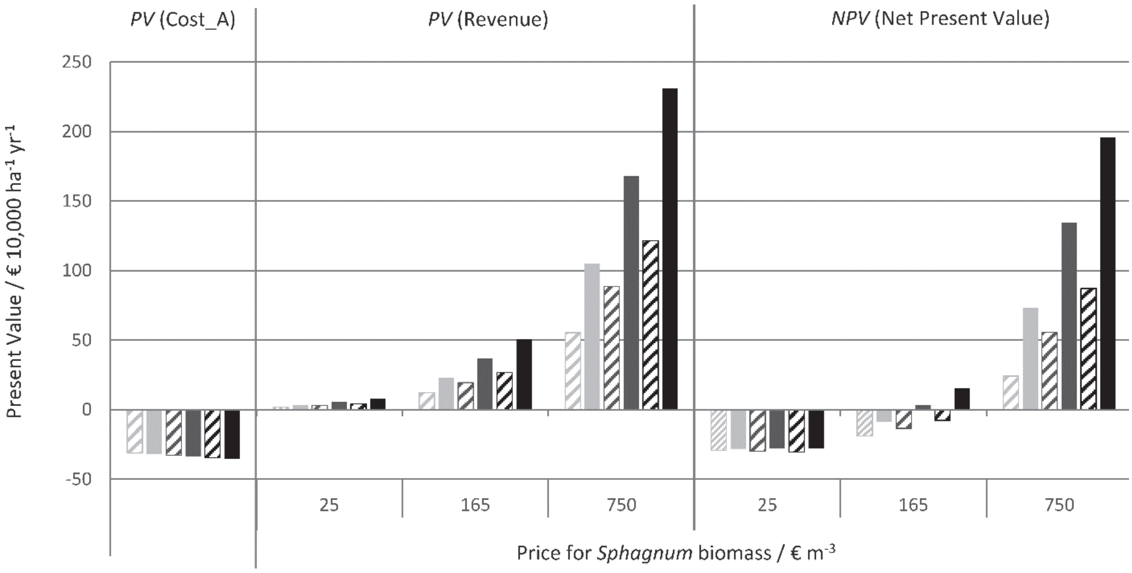

Figure 7. Present Values (*PV*) of Sphagnum farming for high costs (Scenario A) and Revenues and the resulting Net Present Values (*NPV*) according to price level (€ 25, € 165 or € 750), average dry mass yield (light grey: 2.0; dark grey: 3.2; black: 4.4 t ha^{-1} yr^{-1}) and the conversion factor for bulk density (solid fill: 20 g L^{-1}; hatched fill: 38 g L^{-1}).

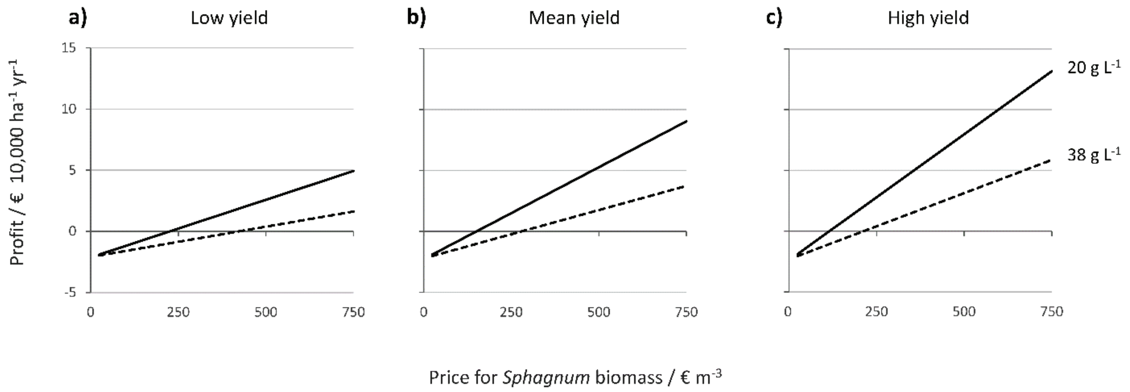

Figure 8. Profitability of Sphagnum farming given as Annuity (T = 20 years; r = 3 %) for Cost Scenario A according to the average dry mass yield (low, mean or high; 2.0, 3.2 or 4.4 t ha^{-1} yr^{-1}), the conversion factor for bulk density (solid line: 20 g L^{-1}; dashed line: 38 g L^{-1}) and the price level (range € 25 to € 750 m^{-3}).

used as a growing medium for orchids (Figure 7, Table A4). The break-even price (Table 2), with a maximum of € 423 m^{-3}, lies well below the € 750 m^{-3} paid for *Sphagnum* shoots used as founder material in Germany. Thus, Sphagnum farming for the production of founder material is profitable even in the most pessimistic scenario of low yield, high bulk density and high costs (Figure 8a). Cheaper founder material has a positive feedback effect that will further reduce the costs of Sphagnum farming, lower break-even prices and improve the competitiveness of cultivated *Sphagnum* biomass.

Potential for cost reduction

We identified a high potential for reducing the break-even price by optimisation and cost reduction (Table 3). The cost of *Sphagnum* shoots as founder material and the investment in water management were the most important cost items during the establishment in 2011 but were, respectively, 41 % and 51 % lower in 2016 (Figure 3). However, these figures still incorporate the high research- and site-specific costs for the electronically controlled automatic water management. The higher costs for site preparation in 2016 compared to 2011 underline the need for reducing topsoil removal, both for limiting GHG emissions from peat soil and for limiting establishment costs. Careful site planning with a dense grid of height measurements and establishing several terraces can minimise peat removal related to levelling the uneven surface. Choosing a cost-efficient irrigation system, minimising topsoil removal, a decreasing price of founder material and scale effects reduce costs considerably (cf. Wichmann *et al.* 2017). Based on current knowledge, a scenario with establishment costs less than € 50,000 ha^{-1} seems feasible (Table A1). Further implementation is required, however, to verify the options for cutting the costs of Sphagnum farming.

Table 2. Break-even price for Sphagnum farming at high cost (Scenario A) and medium cost (Scenario B) according to the harvested yield and bulk density. Prices in square brackets show the effect of an additional non-market income (€ 1300 ha^{-1} yr^{-1}) for Sphagnum farming (DM = dry mass).

	Productivity	DM t ha^{-1} yr^{-1}	3.1		4.9		6.8	
	Average yield	**DM t ha^{-1} yr^{-1}**	**2**		**3.2**		**4.4**	
	Harvested yield	DM t ha^{-1}	10		16		22	
	Bulk density	**DM g L^{-1}**	**38**	**20**	**38**	**20**	**38**	**20**
	Harvested volume	m^3 ha^{-1}	263	500	421	800	579	1,100
Scenario A)	**Break-even price**	€ m^{-3}	423 [397]	226 [212]	278 [262]	150 [141]	213 [201]	115 [109]
Scenario B)	**Break-even price**	€ m^{-3}	330 [301]	177 [163]	220 [204]	119 [111]	170 [159]	93 [87]

Table 3. Key factors for profitability of Sphagnum farming and key uncertainties in calculation.

	Key factors for profitability	Key uncertainties in calculation
Costs	• Availability of founder material (own reproduction or mass propagation) • Cost-efficient irrigation system • Large sites (scale effects) • Minimised topsoil removal • Maximised share of *Sphagnum* production fields compared to infrastructure • Optimised management costs (e.g. weed mowing) • Technological maturity (e.g. adapted machinery)	**Basic assumptions** • Rotation length of 5 years • Total cultivation time of 20 years **Limited data and experience** • Only one pilot site • Only the first 5 years
Revenues	• High productivity • Niche markets with higher prices • Marketing: Top-up by end consumer for renewable growing media • Eligibility for agricultural subsidies • Payments for ecosystem services	**Yield** • Bulk density → harvested volume • Share of remaining biomass • Regrowth potential

Ahead of the high initial costs, management costs were identified as most important for the Present Values (Figure 6a). Optimising weed mowing on the *Sphagnum* production fields seems most promising since it caused the highest costs (41 %, Figure 4). In order to identify cost-efficient management options further research is needed on different machinery (single-axle mower vs. excavator; autonomous vehicles), the mowing regime (frequency, with or without removal of cuttings), influence on *Sphagnum* productivity and coverage of weeds as well as tolerable quantities of non-*Sphagnum* biomass in the growing media. Large-scale harvesting of cultivated *Sphagnum* using an excavator with mowing bucket proved to be a feasible option. Developing alternative mowing machinery that can drive onto the production fields without harming *Sphagnum* productivity would allow reduced causeways and an enlarged share of production area (Wichmann *et al.* 2017).

Uncertainties

While the field trial provided good data on productivity and costs for the first rotation period (five years), major uncertain points of the NPV calculations encompass the harvested volume (few data on bulk density), the assumption on remaining biomass for regrowth and the up-scaling to a total cultivation time of 20 years (Table 3).

Profitability obviously depended on the harvested yield. Additionally, we clearly showed that the bulk density is equally important. Low yields with low bulk density and high yields with high bulk density delivered comparable results (Figure 8). Since the conversion factor is little investigated as yet (Figure 5b, Table A3), it adds uncertainty to the calculations of both revenue and cost. The wide range of dry mass bulk density (for sensitivity analysis we used 20 and 38 g L^{-1}) is confirmed by literature values of 14 and 29 g L^{-1} (Schmilewski 2018), on which basis the values applied in our calculations appear to be comparatively conservative estimates. However, the bulk density of *Sphagnum* biomass needs to be investigated throughout the production chain from field to flowerpot and in relation to *Sphagnum* species, fragment size, moisture content, processing, growing media composition and its stability over lifetime.

Basic assumptions of the investment appraisal still have to be proven by real practice. The optimal rotation length, the regrowth potential and the possible total cultivation time have to be tested. A total cultivation time shorter than 20 years strongly increases annual costs whereas altering the discount rate has limited effect (Wichmann *et al.* 2017). Although we assumed an equal share of biomass remaining for regrowth (35 % of the grown-up biomass) to calculate harvested yields, it is likely that the share is larger in the case of low productivity and smaller in the case of high productivity. Furthermore, to forgo about one third of the grown-up biomass and leave it for regrowth of the *Sphagnum* lawn may turn out to be less feasible and less profitable than to harvest the total biomass and accept the costs of new establishment.

Research on *Sphagnum* productivity, including the selection of species, provenances and breeding, will increase yields (Gaudig *et al*. 2018). Further large-scale Sphagnum farming sites are needed to implement options for cutting costs, to identify further improvements and to enlarge the basis of reliable cost data. Finally, revenues need to cover not only proportionate variable and fixed production costs as calculated in this study but also general, land (purchase or tenure) and marketing costs as well as risk premium and entrepreneurial profit.

Market prospects of *Sphagnum* biomass

'Niche markets'

The price for the produced *Sphagnum* biomass has, not surprisingly, the highest effect on profitability (Figure 8). High-value applications with high revenues allow entry to the European market with the first yields of Sphagnum farming sites at cost-covering prices despite higher initial costs. Next to use as founder material for Sphagnum farming and restoration (regional provenances), 'niche markets' encompass substrates for carnivorous plants, for vivaria with amphibians, reptiles and spiders, or for hanging baskets, wreaths and vegetation walls (Wong *et al.* 2016). The high capacity to absorb and retain fluids and anti-microbial properties offer a wide range of applications. Using *Sphagnum* biomass as insulation and packaging material, for food preservation, medical dressings, nappies and sanitary towels are among traditional (Thieret 1956, Glime 2007) as well as current applications (Zegers *et al.* 2006). Further research on biological properties and compounds will probably pave the way for new utilisation options (Taskila *et al.* 2015) such as, for instance, *Sphagnum* extracts as sources of natural sunscreen (Mejía-Giraldo *et al.* 2015).

Nowadays, the major field of application is the cultivation of ornamental plants, in particular orchids, that turned *Sphagnum* biomass into an international high-value commodity with the image of 'Green Gold' (Orchard 1994). *Sphagnum* moss gathered from wild populations in countries such as Chile, New Zealand, Australia and China is sold mainly to the global centres of orchid production in

Asia like Taiwan, Japan and South Korea (Whinam *et al.* 2003, FIA 2009, INFOR 2010). Europe plays a minor role in the worldwide *Sphagnum* market. In 2009, 72 % of the Chilean export volume went to Asia and only 10 % to Europe (INFOR 2010). In 2018, the total exports from Chile had increased by 19 % in volume and by 60 % in revenues, whereas the share that went to Europe had decreased to less than 5 % of total volume as well as revenues (INFOR 2019). A total quantity of about 9000 m^3 of *Sphagnum* was imported to The Netherlands, France and Germany in the year 2013 (Schmilewski 2017). To produce this amount of *Sphagnum* biomass, 41 to 167 ha of *Sphagnum* production fields with high to low yields (220 m^3 to 54 m^3 ha^{-1} yr^{-1}) would be required. In the light of overexploitation of sensitive peatland ecosystems in the Southern Hemisphere (e.g. Zegers *et al.* 2006) and the long distance transport, sustainably cultivated *Sphagnum* gains a competitive edge on the European market. Niche markets with higher revenues are important to start up commercial scale Sphagnum farming. Addressing larger markets is necessary, however, to establish Sphagnum farming as alternative to predominant drainage based bog grassland farming in North West Germany.

Renewable substitute for peat in horticulture

The medium-term objective of Sphagnum farming is to replace considerable quantities of peat in professional horticulture in order to contribute to phasing out peat extraction. The current price of peat is obviously so low that *Sphagnum* biomass cannot compete (Figure 6), but the market price does not account for the external costs related to peat extraction. European politicians, environmental organisations and consumers are increasingly aware of negative effects such as climate change and biodiversity loss. The acceptance of higher prices for plants grown in peat-free or peat-reduced growing media can be assumed. Since the share of growing media costs in total horticultural production costs is low (< 2 %), increasing its price from € 25 to € 125 m^{-3} would increase the final product price by only 10 %. A break-even price around € 100 m^{-3} seems achievable for cultivated *Sphagnum* biomass (Table 2). The growing media industry already pays higher prices for alternative raw materials, such as € 35–45 m^{-3} for coco products; and the use of coco products nevertheless almost tripled from 2005 to 2013 (Schmilewski 2017). Depleted resources of ‘white peat’ in Central Europe (Schmatzler 2012), the dependence on imports from Scandinavia, Ireland and especially the Baltic countries with higher prices due to increasing labour and transport costs (Falkenberg 2008), and phasing-out plans as discussed already for the UK (Alexander *et al.* 2008, DEFRA 2010), Switzerland (Federal Council of Switzerland 2012, 2017) and Germany (BMUB 2016) will increasingly restrict extraction and utilisation of peat. On functioning markets, shortage increases product prices. Additionally, instruments such as carbon taxation may internalise the external costs of peat utilisation into production costs and thus also increase market prices of peat as well as the economic competitiveness of alternative raw materials in the future.

Although attempts to replace peat date back to the 1980s (Gruda 2012), the application rates of alternative constituents in growing media remain low with an average share of 25 % in Europe and 19 % in Germany (Schmilewski 2017). The share is considerably lower in professional substrates than in potting soils for the hobby market; it was 11 % vs. 27 % for growing media produced in Germany in 2013 (ibid.) compared to 7 % and 6 %, respectively, in 2005 (Schmilewski 2008a), i.e. the use of alternative constituents increased mainly in hobby market products. Raw materials such as green-waste compost, composted bark and wood fibre are limited, however, in their qualitative suitability to fulfil professional demands (Schmilewski 2008b). Critical undesired properties like high pH, high salt content and poor water holding or air capacity need to be compensated by mixing with other raw materials, usually peat (ibid.).

In contrast, *Sphagnum* biomass has similar properties to ‘white peat’, can replace peat at 50 % by volume for most potting substrates and has been successfully used with larger shares up to 100 % in a wide range of horticultural applications (Gaudig *et al.* 2018). In tests with cucumber, tomato and lettuce *Sphagnum* biomass proved to be a better growing medium than ‘white peat’ or mineral wool, leading to a recommendation that *Sphagnum* biomass could be harvested from wild populations in Finland (Silvan *et al.* 2012). In 2016, a total amount of 15,000 m^3 was collected industrially, but technology and logistics still need improvement (Tekes 2017). The environmental impact is reduced compared to peat extraction as stressed by Silvan *et al*. (2017). Nevertheless, collecting *Sphagnum* biomass from living bogs is falsely claimed to be “climate neutral” (Joosten 2017). Removing biomass from (near-)natural bogs prevents it from turning into peat and contributing to the long-term carbon store. Furthermore, an average harvesting depth of 30 cm (Silvan *et al.* 2017) is likely to extract not only fresh *Sphagnum* biomass but also slightly decomposed peat.

While Finland produces 0.9 million m^3 of growing media, Germany is with 8.4 million m^3 the most important producer country and responsible for 24 % of the European production (Schmilewski 2017). Considering the use of ‘white peat’ for growing media production, Germany also ranks first in Europe (23 %), followed by the traditional producer countries Netherlands and Italy as well as Latvia and Lithuania which have been gaining importance since the 1990s (all between 9–12 %) (ibid.). To substitute the current annual German industry demand of ~3.5 million m^3 of ‘white peat’ with cultivated *Sphagnum* biomass, one third of the bog grassland area in Northwest Germany (35,000 ha) would be sufficient (Wichmann *et al*. 2017). In addition, *Sphagnum* biomass may be used in pressed pot substrates (Emmel 2017) to reduce the share of ‘black peat’, i.e. highly decomposed peat, for which the current German industry demand amounts to 3.2 million m^3 (Schmilewski 2017) to 6 million m^3 (Falkenberg 2008). The future demand will be less, however, if other – including not yet known – substitutes become available, if countries and regions currently relying on imported peat-based growing media from Germany start to produce substrates from own renewable resources, and if soil-free plant production methods expand. Ecological issues such as the CO_2 footprint will determine the choice of growing media and cultivation methods in the near future (Gruda 2019).

Is Sphagnum farming an alternative to drained bog grassland?

Sphagnum farming has been proved to be technical feasible. This includes establishing commercial *Sphagnum* cultures on formerly drained bog grassland, ensuring high productivities and using existing machines for harvesting and processing the grown-up biomass. *Sphagnum* biomass is a valuable product for a wide range of applications, especially for the large growing media market. From the farmer’s point of view, there are still major obstacles to Sphagnum farming: founder material is rare, the investment costs are high, first revenues are received only after five years, special machinery is needed, productive land is lost due to the currently high share of infrastructure, European and regional regulations limit the transformation of grassland into permanent cultures, the eligibility for agricultural subsidies is insecure, and incentives for mitigating GHG emissions are missing. In contrast, drained bog grassland for dairy farming is an established land use, considered as typical cultural landscape and supported by agricultural payments. For abandoning current peatland utilisation, Röder & Osterburg (2012) identified short term opportunity costs of € 1700 ha^{-1} yr^{-1} for North West Germany, the highest standard gross margin values across Germany. The long-term profitability, however, which includes covering the costs of dairy cowsheds, machines, labour and land, is highly dependent on public payments, mainly via Pillar I and Pillar II of the EU Common Agricultural Policy (CAP). According to statistical data, 67 % of the ten-year average net profit of € 736 ha^{-1} yr^{-1} for dairy farms located in Lower Saxony was provided by public payments, with the share ranging from 36 % in years with a high milk price to 99 % during the milk price crisis in 2014/15 and 2015/16 (BMEL 2018 and previous years).

From the societal perspective, stopping drainage and raising peatland water levels to the surface is required to contribute to climate protection. To align agricultural policy to climate policy, agricultural subsidies for drainage-based peatland use need to be phased out in a first step and in a second step raising water levels should be prescribed. To initiate the paradigm shift to climate-smart agriculture on peatlands, a set of attractive economic incentives will be necessary such as compensating for the high initial investment, facilitating large-scale implementation by supporting advice and cooperation, long-term schemes remunerating reduced GHG emissions as well as the provision of other ecosystem services and increasing market demand for climate friendly products, e.g. via public procurement (Wichmann 2018). Sphagnum farming is currently the only alternative for rewetted bog sites that combines productive use with substantial peat preservation, but research and development are still at an early stage. This study provided a first micro-economic assessment of Sphagnum farming based on experience at a single pilot site. Further research is needed to improve technical maturity, cut costs and assess the external effects of Sphagnum farming compared to peat extraction and agriculture on drained peatlands. The first results indicate benefits through reduced GHG emissions (Günther *et al.* 2017), sequestered nutrients (Temmink *et al.* 2017) and increased biodiversity (Muster *et al.* 2015, Gaudig & Krebs 2016). Decision making on peatland use alternatives requires a complete picture of costs and benefits for the whole society; the profitability at farm level is only one part of this.

ACKNOWLEDGEMENTS

We thank our project partners for their co-operation and the German Federal Ministry of Food and Agriculture (BMEL), the Ministry for Environment, Energy and Climate Protection of Lower Saxony and the European Regional Development Fund for funding the research projects MOOSGRÜN and MOOSWEIT.

AUTHOR CONTRIBUTIONS

SW collected the cost data, designed and conducted economic analyses and wrote the manuscript. MK and GG mainly supervised the set-up and performance of the Sphagnum farming field trial and contributed data on *Sphagnum* biomass accumulation. SK contributed data on bulk density. All authors revised the manuscript critically before (re)submission.

REFERENCES

Alexander, P.D., Bragg, N.C., Meade, R., Padelopoulos, G., Watts, O. (2008) Peat in horticulture and conservation: the UK response to a changing world. *Mires and Peat*, 3, 08, 10 pp.

Blievernicht, A., Irrgang, S., Zander, M., Ulrichs, C. (2011) Produktion von Torfmoosen (*Sphagnum* sp.) als Torfersatz im Erwerbsgartenbau (Production of peat mosses (*Sphagnum* spp.) as an alternative for peat in professional horticulture). *Gesunde Pflanze*, 4, 125–131 (in German).

Blievernicht, A., Irrgang, S., Zander, M., Ulrichs, C. (2012) The youngest peat - Sustainable production of *Sphagnum* sp. and its use as growing media in professional horticulture. Extended Abstract No. 247, *Proceedings of the 14th International Peat Congress* (Stockholm, Sweden), International Peat Society, Jyväskylä.

BMEL (2018) *Die wirtschaftliche Lage der landwirtschaftlichen Betriebe. Buchführungs-ergebnisse der Testbetriebe des Wirtschaftsjahres 2016/2017* (*The Economic Situation of Agricultural Businesses. Accountancy Data of Test Farms for the Business Year 2016/2017*). Bundesministerium für Ernährung und Landwirtschaft (BMEL), Bonn, 182 pp. Online at: https://www.bmel-statistik.de/landwirtschaft/testbetriebsnetz/testbetriebsnetz-landwirtschaft-buchfuehrungsergebnisse/, accessed 05 Sep 2018.

BMUB (2016) *Klimaschutzplan 2050: Klimaschutz-politische Grundsätze und Ziele der Bundesregierung* (*Climate Protection Plan 2050: Climate Protection Policy Principles and Goals of the Federal Government*). Bundesministerium für Umwelt, Naturschutz, Bau und Reaktor-sicherheit (BMUB), Berlin, 91 pp. Online at: www.bmub.bund.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/klimaschutzplan_2050_bf.pdf, accessed 08 Mar 2019.

Bonn, A., Allott, T., Evans, M., Joosten, H., Stoneman, R. (eds.) (2016) *Peatland Restoration and Ecosystem Services: Science, Policy and Practice*. Cambridge University Press/British Ecological Society, Cambridge, 493 pp.

Brust, K., Krebs, M., Wahren, A., Gaudig, G., Joosten, H. (2018) The water balance of a Sphagnum farming site in north-west Germany. *Mires and Peat*, 20, 10, 12 pp.

Crump, J. (ed.) (2017) *Smoke on Water - Countering Global Threats From Peatland Loss and Degradation. A UNEP Rapid Response Assessment*. United Nations Environment Programme and GRID-Arendal, Nairobi and Arendal, 70 pp.

DEFRA (2010) *Consultation on Reducing the Horticultural Use of Peat in England*. Department for Environment, Food and Rural Affairs (DEFRA), UK, 39 pp. Online at: www.gmmineralsplan.co.uk/docs/NP024.pdf, accessed 08 Mar 2019.

DIN EN 12580 (2014) Soil improvers and growing media - Determination of a quantity. DIN EN 12580:2014-02, 14 pp. Online overview at: https://www.din.de/en/getting-involved/standards-committees/nal/european-committees/wdc-beuth:din21:186297263, accessed 05 Dec 2019.

EC (2017) *CAP Explained. Direct Payments for Farmers 2015–2020*. European Commission, 12 pp. Online at: https://ec.europa.eu/agriculture/sites/agriculture/files/direct-support/direct-payments/docs/direct-payments-schemes_en.pdf, accessed 16 Jul 2019.

Eggelsmann, R. (1986) Subsidence of peatland caused by drainage, evaporation, and oxidation. In: *Proceedings of the Third Symposium on Land Subsidence, Venice*, International Association of Hydrological Sciences Publ. No. 151, 497–505.

Emmel, M. (2008) Growing ornamental plants in *Sphagnum* biomass. *Acta Horticulturae*, 779, 173–178.

Emmel, M. (2017) Torfmoos statt Schwarztorf in Presstopferden - wie viel ist möglich? (*Sphagnum* instead of peat in pressed pots substrate - how much is possible?). *Gemüse*, 11, 18–21 (in German).

Falkenberg, H. (2008) Torfimporte aus dem Baltikum - Bedeutung für die Torf- und Humuswirtschaft in Deutschland (Peat imports from the Baltic States - Importance for the peat and growing media industry in Germany). *Bergbau*, 3, 132–135.

FAO (2014) *Towards Climate-Responsible Peatlands Management* (eds. Biancalani, R., Avargyan, A). Mitigation of Climate Change in Agriculture 9, Food and Agriculture Organisation of the United Nations (FAO), Rome, 117 pp.

Federal Council of Switzerland (2012) *Torfausstiegskonzept* (*Peat Phase-Out Concept*). Bericht des Bundesrates in Erfüllung des Postulats 10.3377 Diener Lenz, 31 pp. (in German). Online at: https://www.newsd.admin.ch/newsd/message/attachments/29089.pdf, accessed 08 Mar 2019.

Federal Council of Switzerland (2017) *Memorandum of Understanding Regarding the Reduction of Peat Use in the Production, Supply and Consumption of Packaged Soils for End Users in Switzerland*. Online at: https://www.bafu.admin.ch/dam/bafu/en/dokumente/wirtschaft-konsum/fachinfo-daten/Absichtserklaerung_Reduktion_Torfeinsatz.pdf.download.pdf/Absichtserkl%C3%A4rung_Torf_Sackerden_Final.pdf, accessed 08 Mar 2019.

FIA (2009) *Resultados y Lecciones en 'Uso y manejo del Musgo* Sphagnum (*Results and Lessons on the Use and Management of* Sphagnum *Moss*). Proyecto de Innovación en XI Región de Aysén, Serie Experiencias de Innovación para el Emprendimiento Agrario, Fundación para la Innovación Agraria (FIA), Spain, 52 pp. (in Spanish).

Gaudig, G., Krebs, M. (2016) Torfmooskulturen als Ersatzlebensraum (*Sphagnum* cultures as substitute habitat). *Biologie unserer Zei*t, 46, 251–257 (in German).

Gaudig, G., Fengler, F., Krebs, M., Prager, A., Schulz, J., Wichmann, S., Joosten, H. (2014) Sphagnum farming in Germany - a review of progress. *Mires and Peat*, 13, 08, 11 pp.

Gaudig, G., Krebs, M., Joosten, H. (2017) Sphagnum farming on cut-over bog in NW Germany: Long-term studies on *Sphagnum* growth. *Mires and Peat*, 20, 04, 19 pp.

Gaudig, G., Krebs, M., Prager, A., Wichmann, S. and 30 others (2018) Sphagnum farming from species selection to the production of growing media: a review. *Mires and Peat*, 20, 13, 1–30.

Glime, J.M. (2007) Economic and ethnic uses of bryophytes. In: *Bryophytes: Mosses, Part 1*, Flora of North America Volume 27, Flora of North America Association, New York and Oxford, 14–41. Online at: http://flora.huh.harvard.edu/FloraData/001/WebFiles/fna27/FNA27-Chapter2.pdf, accessed 03 Jan 2020.

Graf, M., Bredemeier, B., Grobe, A., Köbbing, J.F., Lemmer, M., Oestmann, J., Rammes, D., Reich, M., Schmilewski, G., Tiemeyer, B., Zoch, L. (2017) Torfmooskultivierung auf Schwarztorf: ein neues Forschungsprojekt in Niedersachsen (Sphagnum farming on highly decomposed peat: a new research project in Lower Saxony). *Telma*, 47, 109–128 (in German).

Gruda, N. (2012) Current and future perspective of growing media in Europe. *Acta Horticulturae*, 960, 37–43.

Gruda, N. (2019) Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. *Agronomy*, 9, 298, 1–24.

Günther, A., Jurasinski, G., Albrecht, K., Gaudig, G., Krebs, M., Glatzel, S. (2017) Greenhouse gas balance of an establishing Sphagnum culture on a former bog grassland in Germany. *Mires and Peat*, 20, 02, 1–16.

Hendry, G.A.F., Grime, J.P. (1993) *Methods in Comparative Plant Ecology: a Laboratory Manual*. Chapman and Hall, London, 276 pp.

Hofer & Pautz GbR (2005) *Integriertes Gebiets-Entwicklungs-Konzept Hankhauser Moor* (*Integrated Development Concept for the Hankhauser Moor*). Unpublished report, Hofer & Pautz GbR, Altenberge, Germany, 120 pp. (in German).

Hurlbert, S.H. (1984) Pseudoreplication and the design of ecological field experiments. *Ecological Monographs*, 54, 187–211.

INFOR (2010) *Exportaciones de Productos Forestales No Madereros 2009* (*Exportations of Non-Timber Forest Products 2009*). BOLETÍN N°5, Instituto Forestal Corporacion Nacional Forestal (INFOR), Spain, 18 pp. (in Spanish). Online at: https://wef.infor.cl/publicaciones/pfnm/2010/03/PFNM201003.pdf, accessed 05 Dec 2019.

INFOR (2019) *Productos Forestales No Madereros* (*Non-Timber Forest Products*). BOLETÍN N°33, Instituto Forestal Corporacion Nacional Forestal (INFOR), Spain, 26 pp. (in Spanish). Online at: https://wef.infor.cl/publicaciones/pfnm/2019/03/PFNM201903.pdf, accessed 05 Dec 2019.

Joosten H. (2015) Peatlands, climate change mitigation and biodiversity conservation. An issue brief on the importance of peatlands for carbon and biodiversity conservation and the role of drained peatlands as greenhouse gas emission hotspots. Nordic Council of Ministers. Online at: http://www.ramsar.org/sites/default/files/documents/library/ny_2._korrektur_anp_peatland.pdf, accessed 13 Jun 2019.

Joosten, H. (2017) Harvesting peatmoss from pristine peatlands is bad for the climate. *IMCG Bulletin*, September 2017, 8–9.

Joosten, H., Sirin, A, Couwenberg, J., Laine, J., Smith, P. (2016) The role of peatlands in climate regulation. In: Bonn, A., Allott, T., Evans, M., Joosten, H., Stoneman, R. (eds.) *Peatland Restoration and Ecosystem Services: Science, Policy and Practice*, Cambridge University Press/ British Ecological Society, Cambridge, 63–76.

Krebs, M., Gaudig, G., Matchutadze, I., Joosten, H. (2018) *Sphagnum* regrowth after cutting. *Mires and Peat*, 20, 12, 20 pp.

Kumar, S. (2017) *Sphagnum* moss as growing media constituent: some effects of harvesting, processing and storage. *Mires and Peat*, 20, 07, 11 pp.

Mejía-Giraldo, J.C., Gallardo, C., Puertas-Mejía, M.A. (2015) *In vitro* photoprotection and antioxidant capacity of *Sphagnum meridense* extracts, a novel source of natural sunscreen from the mountains of Colombia. *Pure and Applied Chemistry*, 87, 9–10.

Muster, C., Gaudig, G., Krebs, M., Joosten, H. (2015) Sphagnum farming: the promised land for peat bog species? *Biodiversity and Conservation*, 24(8), 1989–2009, doi: 10.1007/s10531-015-0922-8.

Oberpaur, C., Puebla, V., Vaccarezza, F., Arévalo, M.E. (2010) Preliminary substrate mixtures including peat moss (*Sphagnum magellanicum*) for vegetable crop nurseries. *Ciencia e Investigación Agraria*, 37, 123–132.

Orchard, M.J. (1994) Sphagnum moos - 'Green Gold'. *N.Z. Forestry*, 31–32. Online at: http://nzjf.org.nz/free_issues/NZJF39_2_1994/43385143-5312-4712-9FAE-2F85CAD03AB1.pdf, accessed 08 Mar 2019.

Pouliot, R., Hugron, S., Rochefort, L. (2015) Sphagnum farming: A long-term study on producing peat moss biomass sustainably. *Ecological Engineering*, 74, 135–147.

Röder, N., Osterburg, B. (2012) Reducing GHG emissions by abandoning agricultural land use on organic soils - A cost assessment. Paper prepared for Triennial Conference (Foz do Iguaçu, Brazil), International Association of Agricultural Economists (IAAE), 22 pp.

Schmatzler, E. (2012) Die Torfindustrie in Niedersachsen - Ergebnisse einer Umfrage zur Zukunft der Torfgewinnung in Niedersachsen (The peat industry in Lower Saxony - Results of a survey about the future of peat extraction in Lower Saxony). *Telma*, 42, 27–41 (in German).

Schmilewski, G. (2008a) Peat overs 77 percent of the growing media production in the EU. IPS Commission II survey. *Peatlands International*, 1/2008, 39–43.

Schmilewski, G. (2008b) The role of peat in assuring the quality of growing media. *Mires and Peat*, 3, 02, 8 pp.

Schmilewski, G. (2017) Growing media constituents used in the EU in 2013. *Acta Horticulturae*, 1168, 85–92.

Schmilewski, G. (2018) *Kultursubstrate und Blumenerden - Eigenschaften, Ausgangsstoffe, Verwendung* (*Growing Media and Potting Soils - Properties, Raw Materials, Use*). Flipbook, Industrieverband Garten (IVG), 254 pp. (in German). Online at: https://www.ivg.org/static/flipbook/flipbook.html, accessed 19 Jul 2019.

Silvan, N., Silvan, K., Näkkilä, J., Tahvnonen, R., Reinkainen, O. (2012) Renewability, use and properties of *Sphagnum* biomass for growing media purposes. Extended Abstract No. 55, *Proceedings of the 14th International Peat Congress*, International Peat Society, Stockholm, 6 pp.

Silvan, N., Jokinen, K., Näkkilä, J., Tahvnonen, R. (2017) Swift recovery of *Sphagnum* carpet and carbon sequestration after shallow *Sphagnum* biomass harvesting. *Mires and Peat*, 20, 01, 11 pp.

Taskila, S., Särkelä, R., Tanskanen, J. (2016) Valuable applications for peat moss. *Biomass Conversion and Biorefinery*, 6(1), 115–126.

Tekes (2017) EcoMoss: *Sphagnum* moss is ideal growth medium, ecological and recyclable. Online at: https://www.tekes.fi/en/tekes/results-and-impact/cases1/case-examples-2017/ecomoss-finnish-sphagnum-moss-is-cultivated-into-ecological-products-for-export/, accessed 02 May 2017.

Temmink, R.J.M., Fritz, C., van Dijk, G., Hensgens, G., Lamers, L.P.M., Krebs, M., Gaudig, G., Joosten, H. (2017) Sphagnum farming in a eutrophic world: The importance of optimal nutrient stoichiometry. *Ecological Engineering*, 98, 196–205.

Thieret, J.W. (1956) Bryophytes as economic plants. *Economic Botany*, 10(1), 75–91.

UN (United Nations) (2015) *Paris Agreement*, 25 pp. Online at: http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf, accessed 08 Mar 2019.

Whinam, J., Hope, G.S., Clarkson, B.R., Buxton, R.P., Alspach, P.A., Adam, P. (2003) *Sphagnum* in peatlands of Australasia: Their distribution, utilisation and management. *Wetlands Ecology and Management*, 11, 37–49.

Wichmann, S. (2018) *Economic Incentives for Climate Smart Agriculture on Peatlands in the EU*. Proceedings of the Greifswald Mire Centre 01/2018, ISSN 2627-910X, 38 pp.

Wichtmann, W., Schröder, C., Joosten, H. (eds.) (2016) *Paludiculture - Productive Use of Wet Peatlands. Climate Protection, Biodiversity, Regional Economic Benefits*. Schweizerbart Science Publishers, Stuttgart, 272 pp.

Wichmann, S., Prager, A., Gaudig, G. (2017) Establishing *Sphagnum* cultures on bog grassland, cut-over bogs, and floating mats: procedures, costs and area potential in Germany. *Mires and Peat*, 20, 03, 19 pp.

Wong, J., Dickinson, B., Thorogood, A. (2016) *Assessing the Scale of Sphagnum Moss Collection in Wales*. NRW Evidence Report 185, Natural Resources Wales, 38 pp. Online at: https://cdn.naturalresources.wales/media/685033/report-185-assessing-sphagnum-moss-collection-wales.pdf, accessed 08 Mar 2019.

Yu, J. (2007) *Economically Sustainable Sphagnum Moss Products*. Report to the West Coast Development Trust and the MAF Sustainable Farming Fund, The Horticulture and Food Research Institute of New Zealand Ltd., 41 pp. Online at: https://ecitydoc.com/download/economically-sustainable-sphagnum-moss-products-grant-no-03-087_pdf, accessed 08 Mar 2019.

Zegers, G., Larraín, J., Díaz, F., Armesto, J. (2006) Impacto ecológico y social de la explotación de pomponales y turberas de Sphagnum en la Isla Grande de Chiloé (Ecological and social impact of *Sphagnum* pomponales and peat exploitation in the Isla Grande de Chiloé). *Revista Ambiente y Desarrollo*, 22(1), 28–34 (in Spanish).

Submitted 12 Mar 2019, revision 27 Sep 2019
Editor: Stephan Glatzel

Author for correspondence:
Sabine Wichmann, Institute of Botany and Landscape Ecology, University of Greifswald, partner in the Greifswald Mire Centre, Soldmannstraße 15, D-17489 Greifswald, Germany.
Tel: +49 (0) 3834 - 420 41 43; E-mail: wichmann@uni-greifswald.de

Appendix

Table A1. Costs of establishing a Sphagnum farming pilot site on former bog grassland, given as proportionate cost per partial net production area (€ ha^{-1}).

		Scenario A High costs	Scenario B Medium costs		Outlook Reduced costs
Data from		2011	2016	Compared to 2011	Estimates [c]
Establishment [a]					
- Site preparation	€ ha^{-1}	14,615	36,287	+ 148 %	14,000
- Investment for water management	€ ha^{-1}	45,952	22,334	- 51 %	10,000
- *Sphagnum* shoots[b]	€ ha^{-1}	58,467	34,779	- 41 %	20,000
- "Seeding work"	€ ha^{-1}	8856	5046	- 43 %	5000
Total	***€ ha^{-1}***	***127,862***	***98,446***	***- 23 %***	***49,000***

[a] Establishment cost in 2011, total net production area: 2 ha (cf. Wichmann *et al.* 2017), in 2016 for the extension area of 3.6 ha, total net production area: 5.6 ha.

[b] *Sphagnum* shoots as founder material were bought at a price of € 750 m^{-3} in 2011, costs in 2016 equate proportional costs of cultivating and harvesting own founder material over five years.

[c] Estimates are based on values from year 2011 (site preparation) and 2016 ("seeding work"), a medium break-even price of € 250 m^3 calculated for a total cultivation time of 20 years (Table 3 this study) and a cost-efficient irrigation system (cf. Wichmann et al. 2017).

Table A2. Costs of managing and harvesting a Sphagnum farming pilot site on former bog grassland (1st rotation period: 2011-2016), given as proportionate cost per partial net production area (€ ha^{-1}) and costs of transport and processing of harvested *Sphagnum* biomass (€ m^{-3}).

		1st rotation period (Scenario A - high costs)					
		2011	2012	2013	2014	2015	2016
Management [a]							
- Water management	€ ha^{-1}	2368	1799	3279	2934	2378	1221
- Site maintenance	€ ha^{-1}	1447	5075	10,653	7172	11,772	1897
Total	***€ ha^{-1}***	***3815***	***6874***	***13,932***	***10,106***	***14,150***	***3118***
Harvest							
- Mowing	€ ha^{-1}						5880
- Field transport	€ ha^{-1}	-	-	-	-	-	6772
Total	***€ ha^{-1}***						***12,652***
Transport, Processing							
- Loading [b]	€ m^{-3}	-	-	-	-	-	0.35
- Road transport [b]	€ m^{-3}	-	-	-	-	-	3.20
- Cleaning [c]	€ m^{-3}	-	-	-	-	-	3.24
- Screening [c]	€ m^{-3}	-	-	-	-	-	0.64
Total	***€ m^{-3}***	-	-	-	-	-	***7.43***

[a] Management costs from May 2011 till June 2016, i.e. 62 months in total; for details see Figure 4.

[b] Based on the costs of handling peat: loading with wheel loader at € 75 h^{-1} (20 minutes per lorry) and transporting with lorry and trailer (75 m^3, 21 t additional load) from field site to processing plant (70 km; € 240).

[c] Based on the costs of processing "white peat" in vapour treatment facility and screening line.

Table A3. Mean bulk density of fresh *Sphagnum* biomass (FM g L^{-1}) according to EN 12580 and calculated dry mass bulk density (DM g L^{-1}) in dependence of the water content.

Origin	Predominant species	Sampling Year	n	Processing and storage	Water %	Mean bulk density FM g L^{-1}	DM g L^{-1}
Sphagnum	*S. palustre,*	2013	4	none	93.8	199.5	12.3
farming on	*S. fallax*	2015	3	drying on a concrete slab	28.5	(24.9)[a]	(17.8)
bog grassland,		2015	3	chopping, pressing	87.2	153.3	19.6
NW Germany		2015	3	chopping	91.4	248.7	21.4
		2017	3	storage over winter in the field, vapour treatment, screening: fine fraction	91.5	282.8	24.1
		2017	3	storage over winter in the field, vapour treatment, screening: coarse fraction	87.3	237.6	30.1
Sphagnum	*S. papillosum*	2015	3	drying on a concrete slab	24.1	31.1	23.6
farming on		2015	3	storage in a pile	75.9	108.1	26.1
cut-over bog,		2015	3	storage in a bag	76.0	125.5	30.1
NW Germany		2015	3	vapour treatment, 10 min	84.8	223.6	33.9
		2015	3	vapour treatment, 20 min	78.7	166.6	35.4
		2015	3	vapour treatment, 20 min	82.3	269.9	47.8
Near-natural	*S. fuscum*	2016	3	pressing, screening: coarse fraction	87.5	243	30.4
peatland,		2016	3	pressing, vapour treatment	88.5	269	30.8
Finland		2016	3	pressing	87.0	274	35.5
		2016	n.a.[b]	pressing, screening: fine fraction	87.1	(343)	(44.3)
Mean ± 1 SD							*29.0 ± 9.36*

[a] Measuring the bulk density was hampered by the very dry and brittle biomass.

[b] The value was not measured according to EN 12580 but by the volumeter in the growing media production facility.

Table A4. Present Values (*PV*) of Sphagnum farming at high costs (Scenario A) and medium costs (Scenario B) at different levels of harvested yield, bulk density and price (DM = dry mass). Highlighted cells indicate positive Net Present Values (*NPV*), i.e. profitable cases.

Average productivity	**DM t ha^{-1} yr^{-1}**			**3.1**		**4.9**		**6.8**	
Average yield	**DM t ha^{-1} yr^{-1}**			**2.0**		**3.2**		**4.4**	
Harvested yield	**DM t ha^{-1}**			**10**		**16**		**22**	
Bulk density	**DM g L^{-1}**			**38**	**20**	**38**	**20**	**38**	**20**
Volume	**m^3 ha^{-1}**			**263**	**500**	**421**	**800**	**579**	**1,100**
PV (Cost-A)			€ ha^{-1}	311,734	316,665	328,317	336,207	344,900	355,749
PV (Cost_B)			€ ha^{-1}	243,260	248,191	259,843	267,733	276,426	287,275
PV (Revenue)	**Price (€ m^{-3})**	**25**	€ ha^{-1}	18,436	35,028	29,497	56,045	40,559	77,062
		165	€ ha^{-1}	121,676	231,185	194,682	369,896	267,688	508,607
		750	€ ha^{-1}	553,074	1,050,840	884,918	1,681,344	1,216,762	2,311,848
NPV_A	**Price (€ m^{-3})**	**25**	€ ha^{-1}	-293,298	-281,637	-298,820	-280,162	-304,342	-278,687
		165	€ ha^{-1}	-190,058	-85,481	-133,635	33,689	-77,213	152,858
		750	€ ha^{-1}	241,340	734,175	556,601	1,345,137	871,862	1,956,099
NPV_B	**Price (€ m^{-3})**	**25**	€ ha^{-1}	-224,824	-213,163	-230,346	-211,688	-235,867	-210,213
		165	€ ha^{-1}	-121,584	-17,006	-65,161	102,163	-8,738	221,332
		750	€ ha^{-1}	309,814	802,649	625,075	1,413,611	940,336	2,024,574

Curriculum Vitae

Personal information

has been deleted

for online publication and library copies.

List of author's publications

Journal articles (peer-reviewed papers)

Becker, L., Wichmann, S., Beckmann, V. (**2020**) Common reed for thatching in Northern Germany: estimating the market potential of reed of regional origin. *Resources*, 9 (146), 1–21.

Tanneberger, F., Schröder, C., Hohlbein, M., Lenschow, U., Permien, T., Wichmann, S., Wichtmann, W. (**2020**) Climate change mitigation through land use on rewetted peatlands – cross-sectoral spatial planning for paludiculture in Northeast Germany. *Wetlands*, 40, 2309–2320.

Wichmann, S., Krebs, M., Kumar, S., Gaudig, G. (**2020**) Paludiculture on former bog grassland: profitability of Sphagnum farming in North West Germany. *Mires and Peat*, 26 (08), 1–18.

Ferré, M., Muller, A., Leifeld, J., Bader, C., Müller, M., Engel, S., Wichmann, S. (**2019**) Sustainable management of cultivated peatlands in Switzerland: insights, challenges, and opportunities. *Land Use Policy*, 87, 104019, 1-14.

Geurts, J., van Duinen, G.-J., van Belle, J., Wichmann, S., Wichtmann, W., Fritz, C. (**2019**) Recognize the high potential of paludiculture on rewetted peat soils to mitigate climate change. *Landbauforschung, Journal of Sustainable and Organic Agricultural Systems*, 69 (1), 5–8.

Gaudig, G., Krebs, M., Prager, A., Wichmann, S. and 30 others (**2018**) Sphagnum farming from species selection to the production of growing media: a review. *Mires and Peat,* 20 (13), 1–30.

Wichmann, S. (**2017**) Commercial viability of paludiculture: a comparison of harvesting reeds for biogas production, direct combustion, and thatching. *Ecological Engineering*, 103, 497–505.

Wichmann, S., Prager, A., Gaudig, G. (**2017**) Establishing *Sphagnum* cultures on bog grassland, cut-over bogs, and floating mats: procedures, costs and area potential in Germany. *Mires and Peat,* 20 (3), 1–19.

Milne W, Banwart, SA, Noellemeyer E, Abson DJ, Ballabio C, Bampa F, Bationo A, Batjes NH, Bernoux M, Bhattacharyya T, Black H, Buschiazzo DE, Cai Z, Cerri CE, Cheng K, Compagnone C, Conant R, Coutinho HL, de Brogniez D, de Carvalho Balieiro F, Duffy C, Feller C, Fidalgo EC, Figueira da Silva C, Funk R, Gaudig G, Gicheru PT, Goldhaber M, Gottschalk P, Goulet F, Goverse T, Grathwohl P, Joosten H, Kamoni PT, Kihara J, Krawczynski R, La Scala Jr N, Lemanceau P, Li L, Li Z, Maron P-A, Martius C, Melillo J, Montanarella L, Nikolaidis N, Nziguheba G, Pan G, Pascual U, Paustian K, Piñeiro G, Powlson D, Quiroga A, Richter D, Sigwalt A, Six J, Smith J, Smith P, Stocking M, Tanneberger F, Termansen M, van Noordwijk M, van Wesemael B, Vargas R, Luiz Victoria R, Waswa B, Werner D, Wichmann S, Wichtmann W, Zhang X, Zhao Y, Zheng J, Zheng J (**2015**) Soil carbon, multiple benefits. *Environmental Development*, 13, 33–38.

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*, 16 (13), 1–18.

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

Gaudig, G., Fengler, F., Krebs, M., Prager, A., Schulz, J., Wichmann, S., Joosten, H. (**2014**) Sphagnum farming in Germany – a review of progress. *Mires and Peat*, 13 (8), 1–11.

Jax, K., Barton, D. N., Chan, K. M. A., De Groot, R., Doyle, U., Eser, U., Görg, C., Gomez-Baggethun, E., Griewald, Y., Haber, W., Haines-Young, R., Heink, U., Jahn, T., Joosten, H., Kerschbaumer, L., Korn, H., Luck, G. W., Matzdorf, B., Muraca, B., Nesshöver, C., Norton, B., Ott, K., Potschin, M., Rauschmayer, F., von Haaren, C., Wichmann, S. (**2013**) Ecosystem services and ethics. *Ecological Economics*, 93, 260–268.

Wichtmann, W., Wichmann, S. (**2011**) Environmental, social and economic aspects of a sustainable biomass production. *Journal of Sustainable Energy & Environment*, special issue, 77–81.

Book chapters

Joosten, H., Gaudig, G., Krawczynski, R., Tanneberger, F., Wichmann, S., Wichtmann, W. (**2016**) Paludicultures: sustainable productive use of wet and rewetted peatlands. In: Bonn, A., Allott, T., Evans, M., Joosten, H., Stoneman, R. (eds.), Peatland restoration and ecosystem services: Science, policy, and practice. Cambridge University Press, Cambridge, 339–357.

Wichmann, S., Brander, L., Schäfer, A., Schaafsma, M., van Beukering, P., Tinch, D., Bonn, A. (**2016**) Valuing peatland ecosystem services. In: Bonn, A., Allott, T., Evans, M., Joosten, H., Stoneman, R. (eds.), Peatland restoration and ecosystem services: Science, policy, and practice. Cambridge University Press, Cambridge, 314–338.

Luthardt, V., Wichmann, S. (**2016**) Ecosystem services of peatlands. In: Wichtmann, W., Schröder, C., Joosten, H. (eds.), Paludiculture – productive use of wet peatlands. Schweizerbart Science Publishers, Stuttgart, 13–20.

Schröder, C., Dettmann, S., Wichmann, S. (**2016**) Logistics of biomass production on wet peatlands. In: Wichtmann, W., Schröder, C., Joosten, H. (eds.), Paludiculture – productive use of wet peatlands. Schweizerbart Science Publishers, Stuttgart, 70–76.

Wichmann, S. (**2016**) Economic aspects of paludiculture on the farm level. In: Wichtmann, W., Schröder, C., Joosten, H. (eds.), Paludiculture – productive use of wet peatlands. Schweizerbart Science Publishers, Stuttgart, 109–116.

Wichmann, S. (**2016**) Box 6.1: Supply costs for energy biomass: comparing reed, straw and miscanthus. In: Wichtmann, W., Schröder, C., Joosten, H. (eds.), Paludiculture – productive use of wet peatlands. Schweizerbart Science Publishers, Stuttgart, 112–113.

Wichmann, S. (**2016**) Box 6.2: Costs of establishing paludicultures. In: Wichtmann, W., Schröder, C., Joosten, H. (eds.), Paludiculture – productive use of wet peatlands. Schweizerbart Science Publishers, Stuttgart, 115.

Wichmann, S., Dettmann, S., Dahms, T. (**2016**) Agricultural machinery for wet areas. In: Wichtmann, W., Schröder, C., Joosten, H. (eds.), Paludiculture – productive use of wet peatlands. Schweizerbart Science Publishers, Stuttgart, 64–70.

Wichmann, S. (**2016**) Paludikultur – ausgewogene Sicherung der Ökosystemleistungen genutzter Moore. In: Haaren, C. von, Albert, C. (eds.), Naturkapital Deutschland TEEB-DE. Ökosystemleistungen in ländlichen Räumen – Grundlage für menschliches Wohlergehen und nachhaltige wirtschaftliche Entwicklung. Leibniz Universität Hannover, Helmholtz-Zentrum für Umweltforschung –UFZ. Hannover, Leipzig, 134–137.

Bonn, A., Berghöfer, A., Couwenberg, J., Drösler, M., Jensen, R., Kantelhardt, J., Luthardt, V., Permien, T., Röder, N., Schaller, L., Schweppe-Kraft, B., Tanneberger, F., Trepel, M., Wichmann, S. (**2015**) Klimaschutz durch Wiedervernässung von kohlenstoffreichen Böden. In: Hartje, V., Wüstemann, H., Bonn, A. (eds.), Naturkapital Deutschland - TEEB DE. Naturkapital und Klimapolitik - Synergien und Konflikte. Langfassung. Technische Universität Berlin, Helmholtz-Zentrum für Umweltforschung – UFZ. Berlin, Leipzig, 124–147.

Joosten, H., Gaudig, G., Krawczynski, R., Tanneberger, F., Wichmann, S., Wichtmann, W. (**2015**) Managing soil carbon in Europe: paludicultures as a new perspective for peatlands. In: Banwart, S.A., Noellemeyer, E., Milne, E. (eds.), Soil Carbon. Science, Management and Policy for Multiple Benefits. SCOPE series, 71, CAB International, Wallingford, 297–306.

Bonn, A., Berghöfer, A., Couwenberg, J., Drösler, M., Jensen, R., Kantelhardt, J., Luthardt, V., Permien, T., Röder, N., Schaller, L., Schweppe-Kraft, B., Tanneberger, F., Trepel, M., Wichmann, S. (**2014**) Moore und kohlenstoffreiche Böden: Wiedervernässung als Klimaschutzinvestition. In: Wüstemann, H., Hartje, V., Bonn, A., Hansjürgens, B. (eds.), Naturkapital Deutschland - TEEB DE. Naturkapital und Klimapolitik - Synergien und Konflikte. Kurzbericht für Entscheidungsträger. Technische Universität Berlin, Helmholtz-Zentrum für Umweltforschung - UFZ, Leipzig, 38–43.

Krebs, M., Wichmann, S., Gaudig, G., Joosten, H. (**2014**) Sphagnum farming – paludiculture on degraded bogs in Germany. In: Cris, R., Buckmaster, S., Bain, C., Reed, M. (eds.), IUCN UK - Global peatland restoration demonstrating success, Edinburgh, 22–23.

Wichmann, S., Gaudig, G., Krebs., M., Joosten, H., Albrecht, K., Kumar, S. (**2014**) Sphagnum farming for replacing peat in horticultural substrates. In: Biancalani, R., Avagyan, A. (eds.), Towards climate-responsible peatlands management. Mitigation of climate change in agriculture Series 9. Food and Agriculture Organization of the United Nations (FAO), Rome, 80–83.

Gaudig, G., Wichmann, S. (**2011**) *Sphagnum* as a renewable resource. In: Tanneberger, F., Wichtmann, W. (eds.), Carbon credits from rewetted peatlands. Climate – biodiversity – land use. Schweizerbart Science publishers, Stuttgart, 109.

Monographs and published research reports

Nordt, A., Wichmann, S., Risse, J., Peters, J., Schäfer, A. (**2022**) Potenziale und Hemmnisse von Paludikultur. Hintergrundpapier zur Studie „Anreize für Paludikultur zur Umsetzung der Klimaschutzziele 2030 und 2050“. Hg. v. Deutsche Emissionshandelsstelle im Umweltbundesamt (DEHSt). Berlin, 51 pp.

Schäfer, A., Nordt, A., Peters, J., Wichmann, S. (**2022**) Anreize für Paludikultur zur Umsetzung der Klimaschutzziele 2030 und 2050. Abschlussbericht. Climate Change XX/2022. Umweltbundesamt, Dessau-Roßlau, (in prep).

Wichmann, S., Nordt, A., Schäfer, A. (**2022**) Lösungsansätze zum Erreichen der Klimaschutzziele und Kosten für die Umstellung auf Paludikultur. Hintergrundpapier zur Studie „Anreize für Paludikultur zur Umsetzung der Klimaschutzziele 2030 und 2050“. Hg. v. Deutsche Emissionshandelsstelle im Umweltbundesamt (DEHSt). Berlin, 92 pp.

Hirschelmann, S., Tanneberger, F., Wichmann, S., Reichelt, F., Hohlbein, M., Couwenberg, C., Busse, S., Schröder, C., Nordt, A. (**2020**) Moore in Mecklenburg-Vorpommern im Kontext nationaler und internationaler Klimaschutzziele - Zustand und Entwicklungspotenzial – Faktensammlung. Proceedings of the Greifswald Mire Centre 01/2020 (self-published, ISSN 2627-910X), 33 pp.

Wichmann, S. (**2018**) Economic incentives for climate smart agriculture on peatlands in the EU. Proceedings of the Greifswald Mire Centre 01/2018 (self-published, ISSN 2627-910X), 38 pp.

Dahms, T., Oehmke, C., Kowatsch, A., Abel, S., Wichmann, S., Wichtmann, W., Schröder, C. (**2017**) Halmgutartige Festbrennstoffe aus nassen Mooren. Paludi-Pellets-Broschüre, Universität Greifswald, 2nd updated edition, 68 pp.

Wichmann, S., Wichtmann, W. (eds.) (**2009**) Energiebiomasse aus Niedermooren (ENIM). Projektbericht. Institut für Botanik und Landschaftsökologie. Universität Greifswald. 190 pp. https://mowi.botanik.uni-greifswald.de/doc/paludikultur/projekte/enim/enim_endbericht_2009.pdf

Others journal papers and selected conference proceedings

Wichmann, S. (**2021**) Rewetting – give peat a chance. In: Heinrich Böll Stiftung, Friends of the Earth Europe, Bund für Umwelt und Naturschutz (eds.), Meat Atlas. Facts and figures about the animals we eat. 42–43.

Wichmann, S. (**2021**) Moore – Wiedervernässung als Chance. In: Heinrich-Böll-Stiftung, BUND Deutschland, Le Monde Diplomatique (eds.), Fleischatlas. Daten und Fakten über Tiere als Nahrungsmittel. 28–29.

Hirschelmann, S., Raschke, I., Stüber, M., Wichmann, S., Peters, J. (**2020**) Instrumente für klimaverträgliche Moorbodennutzung: Moorschutz in der Gemeinsamen Agrarpolitik. *Berichte über Landwirtschaft*, 98, Heft 3/2020, 1–32.

Abel, S., Caspers, G., Gall, B., Gaudig, G., Heinze, S., Höper, H., Joosten, H., Landgraf, L., Lange, G., Luthardt, V., Meissner, J.K., Osterburg, B., Padeken, K., Philipp, H.-R., Schröder, V., Strassburger, T., Tiemeyer, B., Trepel, M., van Leerdam, A., Wichmann, S., Wichtmann, W., Wollesen, S., Zeitz, J. (**2016**) Diskussionspapier zur guten fachlichen Praxis der landwirtschaftlichen Moorbodennutzung. *Telma*, 46, 155–174.

Krebs, M., Gaudig, G., Wichmann, S., Joosten, H. (**2015**) Torfmooskultivierung: Moorschutz durch Moornutzung. *Telma*, Beiheft 5, 59–70.

Dahms, T., Wichmann, S. (**2014**) Vom Halm zum Pellet: Bereitstellungsketten für feste Bioenergieträger von nassen Niedermooren. 8.Rostocker Bioenergieforum, Tagungsband. *Schriftenreihe Umweltingenieurwesen*, 45, 441–445.

Hohlbein, M., Wichmann, S. (**2014**) Energie aus dem Moor? – Potenziale für Paludikultur im Thurbruch (Usedom). 8.Rostocker Bioenergieforum, Tagungsband. *Schriftenreihe Umweltingenieurwesen*, 45, 435–439.

Wichmann, S., Gaudig, G., Krebs, M., Joosten, H. (**2013**) Torfmooskultivierung eröffnet neue Perspektiven für Torfersatz und nachhaltige Moornutzung. *Ländlicher Raum*, Zeitschrift der Agrarsozialen Gesellschaft e.V., Schwerpunktheft „Nachhaltigkeit und Regionalität“, 64 (03), 20–23.

Joosten, H., Couwenberg, J., Schäfer, A., Wichmann, S., Wichtmann, W. (**2012**) Perspektiven der Regeneration und Nutzbarmachung von Mooren. *Mitteilungen der Gesellschaft für Pflanzenbauwissenschaften*, 24, 1293–16.

Schröder, Ch., Dahms, T., Wichmann, S., Wichtmann, W., H. Joosten (**2012**) Paludikultur – Ein regionales Bioenergiekonzept für Mecklenburg-Vorpommern. 6.Rostocker Bioenergieforum, Tagungsband. *Schriftenreihe Umweltingenieurwesen*, 32, 69–76.

Wichmann, S., Gaudig, G., Krebs, M., H. Joosten (**2012**) Paludiculture – ecosystem services of Sphagnum farming on rewetted bogs in NW Germany. Conference proceedings, 14th International Peat Congress, Stockholm, Sweden 3-8 June 2012, extended abstract No. 369, 1–6.

Wichmann, S., Tanneberger, T. (**2011**) Paludikultur – Nutzung von Biomasse nasser Moorstandorte: aktuelle Umsetzungsbeispiele aus Norddeutschland und Osteuropa. Konferenz „Energetische Nutzung von Landschaftspflegematerial“, 01./02.03.2011, Berlin, 1–10.

Landry, J., Pouliot, R., Gaudig, G., Wichmann, S., Rochefort, L. (**2011)** Sphagnum farming workshop in the Canadian Maritimes: international research efforts and challenges. *IMCG newsletter*, 2-3/ 2011, 42–44.

Wichtmann, W., Wichmann, S. (**2011**) Paludikultur: standortgerechte Bewirtschaftung wiedervernässter Moore (Paludiculture - site adapted management of re-wetted peatlands). *Telma*, Beiheft 4, 215–234.

Wichtmann, W., Wichmann, S., Tanneberger, F. (**2010**) Paludikultur – Nutzung nasser Moore: Perspektiven der energetischen Verwertung von Niedermoorbiomasse. *Naturschutz und Landschaftspflege in Brandenburg*, 19 (3, 4), 211–218.

Wichtmann, W., Tanneberger, F., Wichmann, S., Joosten, H. (**2010**) Paludiculture is paludifuture: climate, biodiversity and economic benefits from agriculture and forestry on rewetted peatland. *Peatlands International,* 1/2010, 48–51.

Wichtmann, W., Wichmann, S. (**2010**) Paludikultur – Alternativen für Moorstandorte durch nasse Bewirtschaftung. Energetische Verwertung von Niedermoorbiomasse. *Acker+plus*, 5/2010, 86–89.

Wichtmann, W., Wichmann, S. (**2009**) Energetische Nutzung von Niedermoorbiomasse. 3.Rostocker Bioenergieforum, Tagungsband. *Schriftenreihe Umweltingenieurwesen*, 23, 87–99.

Acknowledgements

Once I was told that finishing a PhD thesis proves more one's perseverance than one's ability to independently conduct scientific research. This seems especially true to me when the results already passed the process of peer-review, are published and cited in scientific journals. Late but finally I handed in this thesis as an acknowledgement of inspiring teachers and dedicated colleagues.

Thank you!
Michael Succow set up the interdisciplinary diploma study programme of 'Landscape ecology and nature conservation', which I appreciated as 'delicacies studies'. He also attracted further renowned experts, not the least Hans Joosten as peatland scientist and Ulrich Hampicke as economist. The education in Greifswald provided knowledge of geosciences, biology, land use and economics, law and ethics for a comprehensive understanding of the multi-fold factors influencing our natural environment and motivating for interdisciplinary and transdisciplinary research.

Wendelin Wichtmann opened to me the door to the world of fen paludiculture and supported me with his knowledge, experience and contacts dating back to the times when the term 'paludiculture' was yet not coined.

Greta Gaudig invited me to explore the economics of Sphagnum farming as a newly developing land use option for rewetted bogs. I am very grateful to the whole 'Moosmutzel' working group, to mention also Matthias Krebs, Anja Prager, Franziska Fengler and Mira Kohl, for unforgettable joint field work, visit of conferences, excursions, project meetings and the cheerful company during and after work.

Hans Joosten provided stimuli, trust and encouragement, whenever needed, and agreed to supervise this thesis. Volker Beckmann stepped in to strengthen the economic perspective. Michael Rühs once mentioned the Monte Carlo approach which I happily picked up as a method to deal with uncertainty and variability of economic data of paludiculture. Sharing the office with Regina Neudert ensured enriching discussions on land use science, methods, research approaches and scientific writing.

I sincerely thank all practitioners and companies for their cooperation and support. This thesis was possible only thanks to their willingness to share information, to allow data collection and to discuss procedures and input variables.

The balancing act between fen and bog paludiculture, between the working groups of Peatland Studies and Landscape economics, between pioneering practical implementation, scientific research and peer-reviewed publication as well as communication and knowledge transfer accessible to the interested public, including policy makers, has been a challenge and motivation alike.

The restrictions related to the Covid-19 pandemic with many months of social distancing, home child-care, home schooling and locked-in families caused unknown difficulties of reconciling full-time work and family life and made it hardly possible to find any additional time for writing this synthesis. I thank my beloved ones for their invaluable support, patience and not the least for demanding time for all the other enjoyable parts of life existing next to peatlands.

Special thanks go to all colleagues from the Greifswald Mire Centre – from the university, institute DUENE and the Michael Succow Foundation – for joint vision, high dedication, fruitful inspiration, strong team spirit and enjoyable company, which have been inexhaustible sources of motivation.