Wendelin Wichtmann, Christian Schröder & Hans Joosten (eds.)

Paludiculture – productive use of wet peatlands

Climate protection – biodiversity – regional economic benefits

Schweizerbart Science Publishers

Wendelin Wichtmann, Christian Schröder & Hans Joosten (eds.)

Paludiculture – productive use of wet peatlands

Wendelin Wichtmann, Christian Schröder &
Hans Joosten (eds.)

Paludiculture – productive use of wet peatlands

Climate protection – biodiversity – regional economic benefits

with contributions from 73 authors (see list of contributors on page 263)

Schweizerbart Science Publishers · Stuttgart, 2016

Wendelin Wichtmann, Christian Schröder & Hans Joosten (eds.)

Paludiculture – productive use of wet peatlands

Climate protection – biodiversity – regional economic benefits

Editors: Wendelin Wichtmann, Christian Schröder & Hans Joosten
Greifswald Mire Centre
Ellernholzstraße 1/3
17487 Greifswald
Germany
info@greifswaldmoor.de

This book is a product of the joint research project 'VIP – Vorpommern Initiative Paludiculture' funded by the Federal Ministry of Education and Research of the Federal Republic of Germany within the 'Sustainable Land Management' programme (FKZ 033L030) and the 'Wetlands Energy' Project, funded by EU Aid (DCI-ENV/2010/220-473). The book project was coordinated by the Greifswald Mire Centre (GMC). The GMC is a cooperation of the Ernst-Moritz-Arndt University of Greifswald, the Michael Succow Foundation for the Protection of Nature and the Institute DUENE eV.

Improvement of illustrations:	Stephan Busse
Reference management:	Annie Wojatschke
Translation:	Jenny Schulz, Fernando Andreu, Carl Skarbek, John Couwenberg, Hans Joosten
Proof-reading/review:	Almut Mrotzek, Alma Rodriguez-Tsuda, John Couwenberg
Front cover:	Summer harvest of reed in Peene Valley, Germany. Photo by Christian Schröder

ISBN ebook (pdf) 978-3-50-65479-6
ISBN 978-3-510-65283-9
Information on the English title: www.schweizerbart.com/9783510652839

We would be pleased to receive your comments on the content of this book:
editors@schweizerbart.de

This title is also available in German:
W. Wichtmann, C. Schröder & H. Joosten (Hrsg.): Paludikultur – Bewirtschaftung nasser Moore
Informationen zur deutschen Ausgabe: www.schweizerbart.de/9783510652822

Publisher: E. Schweizerbart'sche Verlagsbuchhandlung (Nägele u. Obermiller)
Johannesstr. 3A, 70176 Stuttgart, Germany
mail@schweizerbart.de
www.schweizerbart.de

∞ Printed on permanent paper conforming to ISO 9706-1994

Layout: DTP + TEXT Eva Burri, Stuttgart
Printed in Germany by Gulde Druck, Tübingen, Germany

Preface by the laureate of the Right Livelihood Award, Michael Succow

Paludiculture – Sustainable use of Wet Peatlands

It is the wet nature of mires, which explains why they were the last natural ecosystems to be taken into intensive agricultural use. This happened to the fens in our Central Europe no longer than 50 years ago. Till this day the vital water is – with large efforts – drained out of the peatlands. All over the world deep drainage continues to cause degradation of organic soils. The rapid depletion of the peat resource inevitably leads to a total loss of the functions of peatlands in the balance of nature, comparable to the loss of soils by desertification in hot climates.

Mainstream drainage-based peatland use has to be challenged fundamentally, because of the ensuing environmental damage and to ensure long-term preservation of agricultural land. In this context one must realise that current unsustainable peatland use in Germany and Europe can only be upheld by large agricultural subsidies. Already long ago I recognized the possibility to utilise biomass of mires without damaging their self-regulative properties and functionality by building upon traditional types of land use such as harvesting reed and using litter from wet meadows.

These ideas were taken up more than 20 years ago, scientifically studied and conceptually tested in various research projects. This led to the emergence of the concept of 'paludiculture', mainly coined by Hans Joosten and Wendelin Wichtmann, environmental scientists from Ernst-Moritz-Arndt-University of Greifswald.

Paludiculture is not merely a word: it is a principle, a rethinking of how to deal with peatlands in agricultural use. This book outlines this new approach to sustainable utilisation of fens for biomass production for the first time in all its complexity.

Paludiculture enables to maintain the peatland carbon stock, whilst at the same time using the land. Paludiculture is about establishing productive, possibly peat accumulating mire-typical plant communities on hitherto deeply drained agriculturally used peatland sites. This environmentally compatible, sustainable land use is urgently demanded as the only future-oriented way for our civilisation.

The prerequisites for these changes are particularly favourable, especially in countries with a high-intensity, peat degrading agricultural peatland use, provided that sufficient water for rewetting is available. An urgent need for action exists for Germany, where drained peatlands annually emit double the amount of CO_2 compared to the entire incoming and outgoing air traffic.

Since my biology studies in Greifswald more than 50 years ago, I am deeply attached to peatlands. I had still the fortune and opportunity to experience mire landscapes in Central and Eastern Europe under peat-preserving low-intensity land use. For me, it is a delayed gratification, a relief to see a new start being made, after 30 years of industrial agricultural peatland use. The end of abuse and the start of new sustainable ways of peatland use – which can only be paludiculture – are long overdue on the way towards a responsible way of managing our ecosystems.

In this pioneering spirit I experience highly motivated, well-educated and well-equipped research teams, that in international networks fathom the new, important knowledge on the functioning and functionality of peatlands in our landscape and that prepare the practical implementation of the results. For "without using nature we cannot exist, but by misusing nature we will perish!"

Gratitude is owed to all those who devote themselves with heart and mind to make amends to the damage to peatlands and who brought together their insight and vision in this book.

Let us give a new future to our peatlands, by restoring the role Nature had meant them to perform in the balance of nature: for the sake of their and our future.

Greifswald, Germany, 2015

Professor Emeritus Michael Succow
Chairman of the Board of the Michael Succow Foundation for the Protection of Nature

Foreword by the Food and Agricultural Organisation (FAO), Martin Frick

The 21st Conference of the Parties of the UN Framework Convention on Climate Change, COP21, concluded in December 2015 with the historic Paris Agreement. As outlined in the Agreement, the international response to climate change should combine efforts to reduce greenhouse gas emissions with those aimed at building resilience, fighting poverty and eradicating food insecurity. The agricultural sectors (crops, livestock, forestry, fisheries and aquaculture) are vital to accomplishing this.

Agriculture, forestry and other land use are responsible for more than 20 percent of all human-induced greenhouse gas emissions. Without concerted and immediate action, this figure will continue to rise in tandem with income and population growth.

The agricultural sectors also provide livelihoods and food security for the vast majority of the world's poor. These sectors are among the most vulnerable to a changing climate. Low-emissions and climate-resilient agricultural growth strategies are therefore vital to effectively tackle climate change, reduce poverty and feed a growing global population.

Peatlands have a particularly important role to play in the fight against climate change. They cover only three percent of global land area, but store 30 percent of the world's soil carbon. When managed unsustainably, peatlands can be a major source of greenhouse gas emissions.

For instance, unsustainable agriculture and forestry activities can drive peatland drainage, which can in turn lower the water table and result in significant greenhouse gas emissions. Drained peatlands are also more prone to fires that emit greenhouse gases and undermine human health and biodiversity.

Conservation and responsible management of peatlands should be top international priorities. Paludiculture is particularly important in this respect. Paludiculture offers a means of cultivating on rewetted peatlands, which reduces greenhouse gas emissions while providing environmental and socio-economic benefits such as reduced frequency of fires, as well as improved livelihoods and food security. Paludiculture can also halt land subsidence, thereby reducing land loss, flood and fire frequency as well as salt-water intrusion.

FAO has long supported better management of peatlands, including through paludiculture. As part of the Mitigation of Climate Change in Agriculture series, FAO and its partners have published guidebooks such as "Towards climate-responsible peatlands management" and "Peatlands – guidance for climate change mitigation through conservation, rehabilitation and sustainable use". Meanwhile, the FAO online collection of peatland management practices provides many examples of projects that are effectively using paludiculture for biomass and energy production.

This new book provides users with detailed and comprehensive information on paludiculture practices. It includes hands-on guidance related to the harvesting, logistics and economics of paludiculture at farm and regional levels. It highlights the need to promote and further develop paludiculture for more widespread adoption.

This publication provides an important basis for more responsible global peatlands management which can be an important element to fighting both climate change and hunger.

Martin Frick
Director
Climate and Environment Division (NRC)
Food and Agriculture Organization of the
United Nations (FAO), Rome

Table of Content

1 Paludiculture as an inclusive solution

Wendelin Wichtmann, Christian Schröder & Hans Joosten

Drainage-based land use of peatlands for agriculture and forestry causes many problems all over the world. Peat soil degradation and subsidence, which are the direct consequences of peatland drainage, progressively decrease the yields and increase the costs to the extent that lands have to be abandoned. Greenhouse gas emissions, loss of biodiversity, and catastrophic peat fires are other consequences of drained peatland use. The massive emissions from drained peatlands worldwide have put them in the international agenda to mitigate climate change (Chapter 10.1; Joosten et al. 2012). Almost all peatlands in Western Europe have been transformed to degrading systems which are now sources of greenhouse gas emissions. Similar processes of peatland degradation are happening in Eastern Europe, America and Asia.

There is an increasing acknowledgment of the fact that problems caused by peatland drainage can only be addressed and solved through raising the water table. Therefore, rewetting and restoration measures have been implemented around the world with the aim to reduce greenhouse gas emissions and to avoid peat fires, as well as to conserve or re-establish peatland biodiversity (Kratz & Pfadenhauer 2001, Kowatsch 2007, Rieley & Page 2008, Tanneberger & Wichtmann 2011).

With rewetting, however, conventional drainage-based agriculture loses the peatland area as productive land. The arisen question is whether degraded peatland can be rewetted and simultaneously be used for production, possibly even with renewed peat accumulation. Management practices have to be found and implemented in a way that links comprehensive peat conservation with the production of renewable raw materials. This is exactly what paludiculture implies (Box 1.1).

Depending on the climate zone, a wide spectrum of plant species can be cultivated in wet peatlands (Box 3.1). Paludiculture includes the traditional uses of semi-natural peatland sites, such as commercial reed cutting or utilisation of litter as bedding material for cattle. Examples of new forms of paludiculture in Central Europe are the use of biomass from reed beds, sedge vegetation, or wet meadows for energy genera-

Box 1.1: What is paludiculture?

Wendelin Wichtmann, Christian Schröder & Hans Joosten

Paludiculture is the agricultural or silvicultural use of wet and rewetted peatlands. Paludiculture uses spontaneously grown or cultivated biomass from wet peatlands under conditions in which the peat is conserved or even newly formed (Wichtmann & Joosten 2007).

Paludiculture differs fundamentally from drainage-based conventional peatland use, which leads to huge emissions of greenhouse gases and nutrients and eventually destroys its own production base through peat degradation (Joosten et al. 2012).

Paludiculture allows the re-establishment and maintenance of ecosystem services of wet peatlands such as carbon sequestration and storage, water and nutrient retention, as well as local climate cooling and habitat provision for rare species (Chapter 5; Joosten et al. 2012, Wichtmann et al. 2010).

Paludiculture implies an agricultural paradigm shift. Instead of draining them, peatlands are used under peat-conserving permanent wet conditions. Deeply drained and highly degraded peatlands have the greatest need for action from an environmental point of view, and provide the largest land potential. The implementation of paludiculture is the best choice for degraded peatlands.

Paludiculture is a worldwide applicable land management system to continue land use on rewetted degraded peatlands. Various plants can be cultivated profitable under wet conditions.

Paludiculture is also a land use alternative for natural peatlands particular for regions where the increasing demand for productive land drives the drainage. Because of their vulnerable ecosystem services, pristine peatlands should best be protected entirely. If land use on pristine mires is unavoidable, paludiculture should always be given preference over drainage-based land use (Joosten et al. 2012).

tion. Additional examples include the plantation of alder on rewetted fens for the production of timber or veneer (Schäfer & Joosten 2005), as well as the cultivation of peatmosses on rewetted bog grassland as a raw material for high quality horticultural growing media (Gaudig & Wichmann 2011, Gaudig et al. 2014) (Chapter 3.1).

For paludiculture to be an alternative to agriculture or forestry on drained peatlands, economic efficiency is of prime importance. Income from paludiculture is generated by the utilisation and sale of biomass, but may also be derived from the provision of other services (e.g. agri-climate and agri-environmental funding programmes, framework contracts for nature conservation, water abstraction charges and carbon credits) and premiums (e.g. direct payments, support for organic farming). Furthermore, biomass from semi-natural vegetation in protected areas can be used if biomass removal is necessary or desirable for habitat and species conservation. In this case, the main emphasis is on conservation, while the harvest of biomass is ancillary.

This book starts with elucidating the negative effects of drainage on the production function of peat soils and their ecosystem services (Chapter 2). With regard to the globally increasing demand for agricultural land to secure food and biomass supply, the world can no longer afford the degradation of peatlands. Faced with an increasing shortage of productive land, we must maintain the productive capacity of the soil and its multifunctionality, and keep options open for the future. The use of above-ground biomass from wet peatlands offers a wide array of perspectives. Valuable raw biomass materials or energy crops can be produced on sites that are not or less suitable for food production. Thus, paludiculture can take away pressure from those areas needed for food production – a potential that is not yet fully quantified. New cultural plants in paludiculture may offer new utilisation opportunities (Chapter 3). New, innovative technical solutions are needed to master the logistic challenges of wet land use and to mobilize the potentials of paludiculture (Chapter 4). Cultivation of wet peatlands stops further peatland degradation, reduces greenhouse gas emissions, supports wetland biodiversity and secures or restores various important functions within the regional water and nutrient cycle (Chapter 5).

Profitability is of crucial importance for the implementation of paludiculture as a new land management concept. For business and regional development, the utilisation of biomass from wet peatlands offers various interesting economic prospects (Chapter 6). Since a change to paludiculture implies a paradigm shift in land management, the framework of legislation and agricultural policy must be adapted to this new land use concept. The recognition of paludiculture as a new form of land management is paramount for its large-scale implementation in the European Union. Ideas how to overcome existing obstacles and how to provide incentives for the implementation of paludiculture are proposed in Chapter 7.

When implementing paludiculture, the interests of the local population must be taken into consideration, as the landscape may change substantially in appearance when peatlands are rewetted. Information provision and goal-directed communication between all parties involved are urgently needed prior to the implementation of paludiculture. Conflicting interests can be identified through new participatory approaches, and solutions to problems and conflicts can be developed together with the local stakeholders (Chapter 8). Furthermore, the book contains advice on how to implement paludiculture in practice and what steps must be considered during planning (Chapter 9). Case studies are presented to show how the decision to implement paludiculture can arise from various motives (Chapter 10). Last but not least, it is important to learn from existing paludiculture projects, because we are just entering a new era of peatland management (Chapter 11).

This book shows the need for a broad, interdisciplinary approach to facilitate a land use change on peatlands. Expert knowledge from various fields must be combined with practical experience. Paludiculture has many facets, and the most important ones are described and discussed in this book. Other questions will only be touched upon superficially, as much experience is still lacking. Doubtlessly, paludiculture remains a big challenge for scientists, decision makers and practitioners alike. But the first important steps have been set.

2 The limits of drainage based peatland utilisation

Knowledge, as well as the quality and availability of means of production, determine the nature and intensity of all land use (Jutta Zeitz, 2015).

In the past, human impact on peatlands has varied depending on existing technology, human needs and financial means. Peatlands were exploited in order to extract peat for fuel but the main interest was to turn them into agricultural use. Often, the reclamation of peatlands was linked to political changes – e.g. to win new land for settling refugees. Large-scale cultivation efforts were driven and funded by state policy – for instance, the Cultivation Act (Urbarmachungsedikt) of Frederick the Great and the complex amelioration (Komplexmelioration) in the German Democratic Republic (Chapter 2.1). However, regardless of motivation and techniques, the precondition for peatland cultivation was always to drain the water away from the naturally wet peatlands.

Drainage leads to alteration and intensification of the transformation processes in the upper peat layer (Chapter 2.2), which, dependent on their nature and intensity, leads to changes in soil productivity (Chapter 2.3). This 'secondary pedogenesis' in drained peatlands is similar in all climate zones. In the beginning and with shallow drainage, soil productivity may initially even improve. On the longer term, however, deep drainage, frequent ploughing and the sowing of cash crops result in such profound changes of the physical, chemical and biological properties of the soil, that the peat soil degrades. Not only the conditions for biomass production deteriorate, but also other ecosystem services of mires, such as water retention and the sequestration and storage of nutrients and carbon are negatively affected (Chapter 2.4). As these changes are largely irreversible, drainage based land use of peatlands is neither ecologically nor economically sustainable. Long term peatland utilisation is only possible when agriculture is adapted to the natural site conditions and not the other way around, as it was the case during past centuries.

2.1 Fen peatland use in Northeast Germany

Jutta Zeitz

Peatlands form by the accumulation of peat, when the production of biomass is larger than its decomposition. This is the case when decomposition is retarded by oxygen depletion caused by a permanently water-saturated environment.

Whereas in many regions mires were the last areas to be taken into cultivation, archaeological evidence shows that already Palaeolithic hunter-gatherers made use of peatlands. However, this usage did not significantly impact peat formation and the ecosystem services mires provided. Before humans started to change the water balance of mires intentionally, they used them, and particularly their margins, in several ways: as pasture, for hay making or for gathering litter, especially in dry years (Fischer 1999). The biomass was mown by hand and transported onto mineral ground, whereas animals were driven onto the mires for grazing if the load-bearing capacity of the ground allowed it. Later, peatlands also became providers of fuel peat and a variety of raw materials, including salt (extracted from saline peat in coastal mires), bog iron ore, and bog lime (Succow & Jeschke 1986, Succow 1988, Lehrkamp & Zeitz 2014). The deforestation of large areas, as well as pondage for watermills, changed the regional hydrology and even stimulated the growth and expansion of mires.

In Northeast Germany and other parts of West and Central Europe mires have increasingly been modified by agricultural use in the course of the last 300 years. Mires were drained to be used as pasture, hay meadow or arable land. Depending on the nature and intensity of the practices the effects on the mires range from small to irreversible (Table 2.1).

Drainage improves the trafficability of the ground, whereas the altered microclimate reduces the frequency of early and spring frosts. Peat decomposition and mineralisation result in the release of plant nutrients, especially nitrate. Fertilisation and management enable the cultivation of crops that are specifically bred, highly productive, but thus also more demanding to site conditions.

Table 2.1: History of agricultural use of fen peatlands in Northeast Germany (changed after Succow 1988 and Zeitz 2003, Zeitz 2014). Floodwater and water rise mires were in many cases the first mires to be cultivated, followed by percolation mires.

Time	Typical utilisation/Example
6th century	• Very low intensity pastoral use of sedge vegetation
13th century	• Mowing of graminoid vegetation of eutrophic floodwater mires • Use of litter from sedge vegetation • Beginning drainage and establishment of hay meadows (1 cut per year) by Cistercian monks
18th century	• Extension of fen grassland by drainage and clearance of swamp forests • Water regulation of rivers and drainage of large valley mires • First establishment of polders • 1718 drainage of the Havelländisches Luch, initiated by Frederick William I • 1765 Cultivation Act (*Urbarmachungsedikt*) for peatland cultivation in Prussia issued by Frederick II
19th century	• Drainage using fascines (from the mid-19th century) • Land gain by lowering the water table of lakes • Valley mires are largely converted to humid meadows • Development of humid *Molinia* (Purple Moor Grass) meadows caused by removal of plant nutrients • Start of fen cultivation by covering the peat with sand (sand cover cultivation, *Sanddeckkultur*, 1817, C. Pogge) • Beginning of Rimpau sand cover cultivation (*Moordammkultur* 1887)
20th century, until the mid 1960s	• Application of artificial fertilisers • Development of humid meadows that are cut twice per year (hygrophilous tall herbaceous communities with *Cirsium oleraceum*) • Development of high quality cultivated grassland • Yields of up to 8.5 t dry mass ha^{-1} for fen grassland
mid 1960s	• Complex amelioration: renewed and very deep drainage by lowering the groundwater table to 50–80 cm and more below the ground surface • Intensive grassland use with high rates of fertilisation (100–200 kg N ha^{-1}) • Tilling and renewed grass cultivation every 4–5 years. Yields reach 10 t ha^{-1} dry mass ha^{-1} a^{-1} with 3–4 cuts per year • Partially arable use on deeply ploughed areas
Since the mid 1970s	• Increasing peat degradation on intensively used grassland • Technical upgrade of drainage infrastructure for water regulation in both directions (drainage and irrigation)
1990 until the end of the 20th century	• No further large scale ameliorations • Peatland use becomes increasingly problematic due to waterlogging, wind erosion and the development of microrelief • Increasing conflicts with respect to water regulation (usage rights for water abstraction, high costs for pumping, insufficient maintenance, soil wetness) • Abandonment for economic reasons • Rewetting for nature conservation
21st century	• Partly renewed intensification to secure peatland utilisation • Minimum maintenance, peatlands become areas of marginal agricultural revenues • Intensification of problems related to peatland utilisation • Rewetting in order to reduce greenhouse gas emissions

In the following sections we present some common practices of peatland utilisation in Northeast Germany.

2.1.1 Niedermoorschwarzkultur (black fen cultivation)

Black fen cultivation is the oldest form of intensive land use on peatlands in Germany, being widely practiced since the 13th century until now. The German name 'Niedermoorschwarzkultur' (Niedermoor = fen, schwarz = black, kultur = cultivation) derives from the black top soil which results from peat oxidation after drainage. This form of land use involves drainage of the peatland, removal of the natural vegetation and ploughing of the top peat layer. Subsequently, the soil is fertilised: in earlier times, solid and liquid manure were used whereas in modern times, mineral fertiliser is utilised. After fertilisation, specially bred crops are sown. In this form of land use the soil profile stays largely intact (Figure 2.1).

Fens were initially drained by shallow ditches that were dug manually and quickly collapsed. Later, ditches with a wide range of depths and widths plus subsurface drainage tubes were used. Up until the end of the 19th century all drainage ditches and channels were dug by hand (Figure 2.2). Clay drainage pipes from mecha-

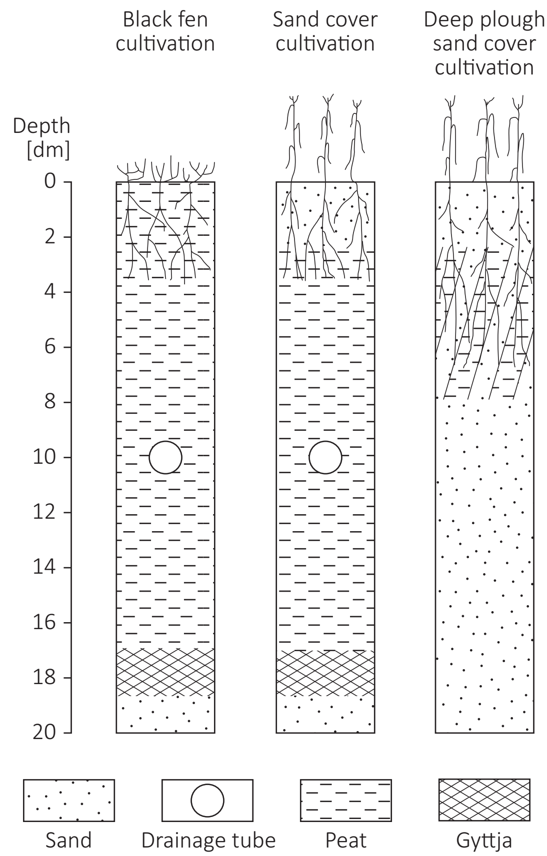


Figure 2.1: Soil profiles and root penetration in various fen cultivation alternatives (after Göttlich & Kuntze 1990).

Figure 2.2: Adolescents digging a drainage ditch in the Friedländer Große Wiese, Germany (Zentralbild Schwankler, 11.8.1958).

nised mass production were available and used in fen drainage since the mid 19th century. From the 1960s onwards the clay pipes were replaced by plastic pipes. In Northeast Germany, subsurface drainage of fens was also accomplished by cutting rectangular (18 cm x 14 cm) tunnels below ground (Figure 2.3), a practice called ‘Maulwurfsfräsdränung’, (Maulwurf = mole, Fräsen = cutting, dränung = drainage). These pipe-less drains were functional for about 10 years (Scholz 1986).

Currently, many of the formerly laid drainage pipes lay close to the ground surface, which illustrates the large peat losses associated with land use based on drainage. Colour picture 1 shows an example where 50 years of drainage has caused the loss of 100 cm of peat (as a consequence, drainage tubes originally installed at 120 cm depth lay now close to the surface) and a (black) degraded top soil is overlying the originally less decomposed bog peat.

2.1.2 Sanddeckkultur (sand cover cultivation)

In the 19th century, farmers observed that the soil properties of cultivated fen peatlands improve when the peat is covered with sand. For such ‘Sanddeckkultur’ (sand cover cultivation), sand is spread on top of the fen peat without mixing sand and peat. The stratigraphy of the underlying peat profile itself is not altered (Figure 2.1). A special technique applied in Mecklenburg, was ’Poggeln’, named after its inventor Carl Pogge (1763–1831). In 1817, Pogge applied this technique for the first time on a 10 ha peatland meadow of his manor, near the town of Güstrow. The method involved covering the peatland meadow with sand brought from the margins of the peatland by cart. A sand layer of about 12–15 cm was spread onto the turf of the shallowly drained peatland. The weight load of the sand layer compressed the underlying peat, kept it

Figure 2.3: 'Maulwurfsfräsdränung' (mole pipe drainage) in the Friedländer Große Wiese 1971 (Zentralbild Bartocha, 26.4.71).

moist and reduced peat mineralisation (Ratzke & Mohr 2005). Later research has shown that in comparison to the aforementioned 'Niedermoorschwarzkultur' peat mineralisation rates at a mean water level 90 cm below ground are reduced approximately by half when the peat is covered with a sand layer (Mundel 1976).

The initial sandy cover layers were often heterogeneous in thickness. In the course of time, they got mixed with the underlying peat through very deep ploughing, and changed into a mixture of sand and peat. This process offset the positive effects of the 'Sanddeckkultur' in regard to soil productivity, workability, and peat mineralisation.

An improved form of Pogge's method was developed by Theodor Herrman Rimpau on his manor in Cunrau (Saxony-Anhalt) in 1862. The practice was called 'Moordammkultur' (Moor = peatland, damm = dam, kultur = cultivation, Figure 2.4). In this method, the fen peatland was deeply drained by a dense network of ditches. The area was divided in 25 m wide fields on which the peat from the ditches was evenly spread. Lastly, the fields were covered with a 10–12 cm layer of mineral soil (sand) material, which in shallow peatlands was taken from the ditches whereas in deep peatlands, it was taken from the surrounding mineral area. Around 1900 this technique was considered an excellent method to transform grassland areas with poor soil productivity into higher yielding arable land. Only shallow tilling was allowed to prevent the mixing of the mineral soil layer with the underlying peat. However, even with this method, the drainage was too deep to conserve the peat layer (Massenbach 1887: 'It is sufficient to lower the water table to 1 m below ground'…), resulting in shrinkage and peat degradation (Göbel 2000).

2.1.3 Tiefpflugsanddeckkultur (deep plough sand cover cultivation)

The 'Tiefpflugsanddeckkultur' (Tiefpflug = deep plough, sanddeck = sand cover, kultur= cultivation) form of peatland cultivation exists since the 1950s. A giant plough was used to plough shallow and already drained fen peatlands, so that the peat layer was mixed with the underlying sand (Figure 2.1, Colour picture 2). In the same action the fields were covered with an approximately 25 cm thick sand layer and subsequently used for mainly arable farming. The peat stratigraphy was

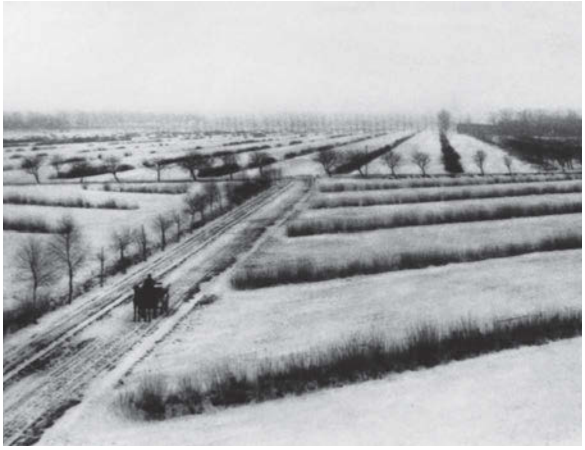


Figure 2.4: Rimpau sand cover cultivation (German: 'Rimpausche Moordammkultur) around 1900.
https://upload.wikimedia.org/wikipedia/de/1/1a/Rimpauische_Moordammkultur_um_1900.jpg

completely disturbed by the ploughing, which strongly improved vertical water exchange in the profile, particularly on sites with impervious, water stagnating lake sediments. Compared with the 'Niedermoorschwarzkultur', the soil achieved a higher load-bearing capacity and fields were less prone to the proliferation of weeds. 'Tiefpflugsanddeckkultur' was applied to approximately 2,500 ha of land in Northeast Germany and has altered these former peatlands structurally in such a way that they cannot be classified as peatland anymore, although they remain groundwater dependent (Zeitz 2003, Zeitz 2014).

2.1.4 Komplexmelioration (complex amelioration)

'Komplexmelioration' was applied in East Germany from the 1960s until the 1980s, when many formerly shallowly drained fen peatlands were further 'ameliorated' by a variety of interventions. Part of the existing drainage channels were deepened until 2.5 m, whereas the fields were enlarged by filling in the remaining ditches between the large and the deep ones. Since the 1950s, national engineering standards guaranteed the standardization of ditch distances, depths and slope gradients, taking into account the hydraulic conductivity of peats and lake sediments, the presence of impervious layers, as well as the requirements of future land use. Smaller fields were merged to larger ones because large coherent fields are favourable in technical and economic terms. This also reduced the number of vehicle crossing points between fields thus reducing their high maintenance costs.

Several extreme summer droughts in the 1970s and the first signs of peat degradation on the overly drained fen peatlands lead to the installation of adjustable weirs in the ditch system, which allowed drainage, water retention and irrigation. Water retention by elevated weir levels made it possible to keep the water table high until May, that is to say, four to six weeks longer than before. However, these high spring levels could not prevent desiccation in summer (Box 9.4). Thus, irrigation was widely practiced but required additional water supply by pumping water from higher laying water courses. For the large Oberes Rhinluch peatland area in the federal state of Brandenburg, water was transported from lake Müritz via a chain of smaller lakes. This resulted in significant ecological damage due to falling lake water levels. The effect of irrigation was very limited, especially on degraded peatlands. Even though shrinkage cracks had developed in the drained peat, irrigation had little effect, probably because sealing (colmation) the ditch walls and compaction prevented water from entering the peat body (Hennings 1995).

2.2 Drainage induced peat degradation processes

Jutta Zeitz

For over 200 years the processes that follow on peatland drainage have been observed and documented. Initially, this monitoring was driven by concerns as to whether and how the newly drained areas would become utilisable. During the 1960s and 1970s, research was encouraged because secondary soil genesis in drained peatland prevented efficient drainage and required recurring intervention. Since the early 1980s, conventional drainage-based land use of fen peatlands became subject of critical public debate (Schmidt et al. 1981).

Drainage interrupts the primary process of soil genesis in peatlands, namely peat formation. Instead, peat accumulation is replaced by secondary pedogenetic processes including consolidation, compaction, shrinkage, humification and mineralisation (oxidation), as well as dislocation, leaching and accumulation of soil substances. The continuously decreasing soil productivity resulting from these processes challenges the long-term utilisation of peat soils under conventional agriculture (Sauerbrey & Zeitz 2003, Stegmann & Zeitz 2001, Zeitz 2001, Ilnicki & Zeitz 2003, Oleszczuk et al. 2008, Kalisz et al. 2010, Zeitz 2014).

While initially (i. e. in the first years) consolidation is the main process causing the lowering of the peatland surface upon drainage, subsequently other processes, including shrinkage, compaction and mineralisation (peat oxidation) contribute more significantly. Subsidence is the sum of all processes that lower the peatland surface.

2.2.1 Peatland consolidation

Pristine mires consist of peats and organic sediments that are, in general, extremely porous. In pristine state, peatlands are – with the exception of seasonal water level fluctuations, saturated with water up to the surface. Peatland drainage empties the pores and causes a purely mechanical setting of the peat because the buoyancy is lost. This loss leads to the compression of the formerly spongy peat and to a reduced peat porosity (Table 2.2). The load of the drained peat at the surface also causes compression of the underlying peat strata that are still saturated with water. As a result of these processes that occur immediately after drainage, the surface of the peat strongly subsides. The more porous and spongy the peat in pristine state is, the smaller the volume of the drained peat will be. Similarly, the thicker the peat layer and the deeper the drainage, the more the surface will be lowered. For example, when a typical percolation mire with a dry matter content of 7.5% and a thickness of 5 m is drained to a water level of 1.1 m below the original surface, subsidence may reach 0.9 m (Eggelsmann 1981). Any further drainage leads to renewed consolidation, though less dramatically, as the peat layer has already lost large amounts of water and therefore has a higher content of dry matter. In order to calculate the magnitude of consolidation, empirical formulas were developed and the depths of drainage ditches and drain pipes were accordingly positioned (Segeberg 1960, Eggelsmann 1981).

Table 2.2: Change of soil properties as a result of drainage and intensive agricultural use of fen soils and their effects on provisioning services (after Zeitz 2014).

Trend	Soil property	Direct and indirect effects
Increasing	Bulk density	• Improved load-bearing capacity and trafficability • Restricted movement of water and nutrients • Formation of plate-like aggregates impermeable to water, which cause flooding after heavy rain and may induce vegetation dieback
	Air filled pore space, mainly as cracks and tears in the top soil	• Strong heating up caused by increased insulation and possibly resulting vegetation dieback
	Concentration of nutrients in the top soil	• Uneven nutrient supply and shallow root penetration with higher risk of drought
	Microrelief	• More difficult movement of vehicles • Strong alterations in soil moisture • Reduced possibilities for water regulation
	Vulnerability to wind erosion	• Loss of nutrient rich top soil • Increase in fine dust emissions (particulate suspended matter, PSM) • Soiling of cultivated plants, water bodies and roads (on-site and off-site damage by erosion)
Decreasing	Saturated and unsaturated water conductivity	• Restricted water regulation • Decreased capillary water rise • Increased risk of droughts
	Storage capacity of plant available water	• Reduced yield
	Rewettability	• Top soil becomes hydrophobic • Microerosion and particle translocation after precipitation • Increasing heterogeneity of the soil
	Ground surface height	• Gravity drainage becoming increasingly difficult • Polders (with dikes and pumps) become necessary • Increased flood risk; in coastal areas also intrusion of and flooding by salt or brackish water
	Peat thickness	• Impeded water regulation and storage • Decline of filter and storage capacity for pollutants • Disappearance of peat layer and exposure of underlying unproductive soil (gyttja, acid sulphate soils, hard pan, quartz sand)

2.2.2 Shrinkage

Peats and organic lake sediments are porous and elastic substrates that shrink when they lose water. In pristine mires these processes are – within the range of natural water level fluctuations, reversible, i. e. a rise in the water level causes the peat layers to swell back to their original volume. The consequent oscillation of the mire surface is called 'Mooratmung' (German for 'bog breathing'). If desiccation exceeds a certain threshold (depending on the type of peat), shrinkage becomes largely irreversible. The dry matter content of the peat increases, and cracks and clefts appear in the peat. Depending on the peat type and the original degree of peat humification, vertical and horizontal fissures of varying dimensions develop. The more porous the peat was in pristine state, the stronger its volume reduction by drainage. Repeated shrinking and swelling lead to the development of characteristic segregation structures (Zeitz 1992). Long-term and intensive desiccation – reinforced by mechanical disturbance by tillage, results in a very fine grainy, dusty structure in the top soil, with high water repellency (Zeitz & Velty 2002).

2.2.3 Humification and mineralisation

Simultaneously with consolidation, compaction and shrinkage, also microbiological decomposition starts to take place in the oxygenated peat layers. During humification, degradation-resistant organic substances are converted into humus, whereas during mineralisation, decomposition to simpler anorganic substances takes place. Fertilisation, in particular with nitrogen, accelerates humification and mineralisation ('priming effect', Paepke 1992). Organic matter is converted into end products with simpler molecular structure, which are released from the peatland as gases (CO_2, N_2O) or as solutes (nitrate, dissolved organic carbon – DOC), which leach out or are transported into deeper peat strata. Mineralisation results in loss of organic matter and contributes to the continuous subsidence of the peatland surface (Leifeld et al. 2011).

2.2.4 Translocation, leaching and concentration of organic material

The enhanced break down of organic matter by soil macrofauna, followed by humification and mineralisation, enable the translocation and – depending on the thickness of the peat layers, also the leaching of smaller particles and soluble substances. As a result of subsidence, shrinkage, compaction and mineralisation, easily adsorbable plant nutrients such as phosphorus accumulate in the top soil. The translocation of soil particles, the cycle of thawing and freezing, as well as soil compression by heavy agricultural machinery may result in soil compaction and the formation of stagnating layers in the top soil that cause waterlogging (Zeitz et al. 1987).

2.2.5 Soil development after drainage

Drainage results in surficial peats that are highly decomposed by secondary decomposition, in which the original plant structures are no longer recognisable. The processes described above lead to the development of typical soil horizons, such as the shrinkage-induced 'peat crumb horizon' in the deeper soil strata. In case of shallow drainage, the top soil is 'earthified' (secondarily humified), with the peat structure consisting of crumbles that are greasy when wet, and hardly dusty when dry. Deep drainage causes the peat to become 'strongly earthified', fine granular, greasy-granular when wet and dusty-granular when dry. The German Soil Classification distinguishes between these soil types in drained peatlands as 'Erdniedermoore' and 'Mulmniedermoore', respectively (Sponagel 2005, Figure 2.5).

2.3 Impact of drainage on productivity

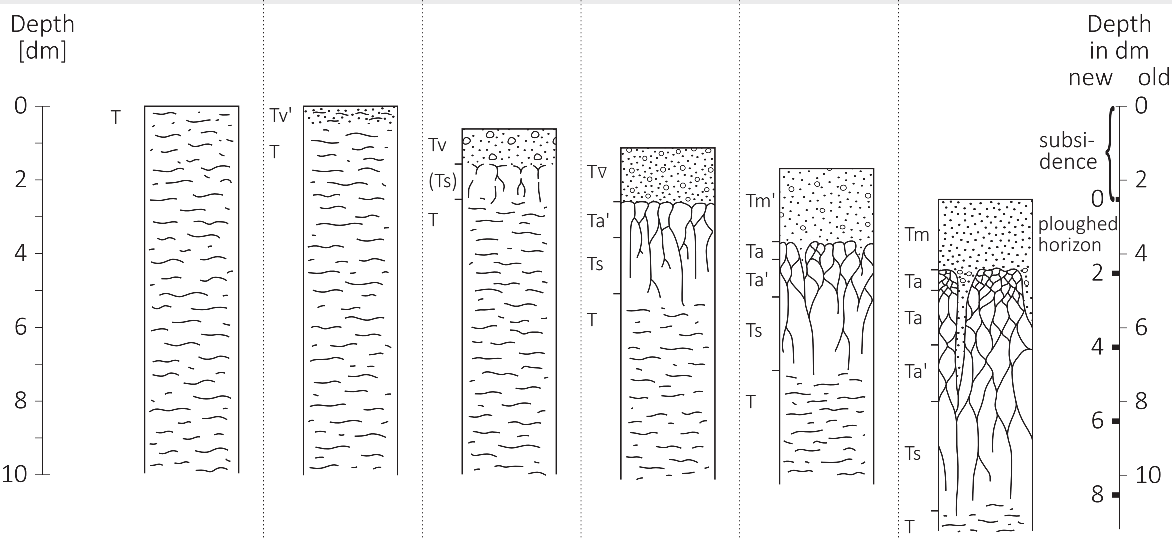
Jutta Zeitz

Soil productivity of drained fen peatlands is determined by a number of site conditions that in mutual interdependency determine trafficability, water retention and effective yield, nutrient retention and supply, and soil aeration and thermal regulation. Secondary pedogenesis, which begins with drainage and intensive agricultural use, influences these site conditions and consequently soil productivity. The impact of the interrelated processes resulting from drainage leads to considerable land management problems, and questions the productive land use on these sites (Table 2.2).

2.3.1 Consequences of peatland drainage

Peatland subsidence resulting from consolidation, shrinkage, compaction and mineralisation significantly complicates water management. Subsidence in temperate regions is 2–25 mm per year, depending on site conditions (peatland type, peat type, hydrology and climate); drainage intensity (time, duration and depth of water level drawdown); and land use (grassland or arable use) (Mundel 1976, Schothorst 1977, Lehrkamp 1987, Eggelsmann 1990a, Fell et al. 2015). In Southern Europe or Southeast Asia, subsidence can reach up to 70 mm per year (Hooijer et al. 2012) (Box 2.1). In some locations, subsidence has been systematically monitored by means of stakes placed in the ground to mark the former land surface.

	1 Peat accumulating fen	2 Shallowly drained fen	3 Moderately drained fen	4 Deeply drained fen	5 Slightly degraded fen	6 Heavily degraded fen



	1	2	3	4	5	6
(Secondary) pedogenesis:	Peat formation	Weakly humified	Moderately humified	Strongly humified	Weakly earthified	Strongly earthified
Summer water level [dm below floor]:	Near surface	1-2.5	2.5-4.5	4.5-7	7-10	10-15
Potential capillary fringe [dm]:	> 6	> 6	≥ 5	4-5	3-4	< 3
Moisture class:	5+ Wet	4+ Very moist	4+ 3+ Very moist to moist	3+ 2+ Moist to moderately moist	2+ 2- Moderately moist to moderately dry	2- Moderately dry

Figure 2.5: Pedogenesis on fen peat as a function of drainage depth and time. Consolidation at the beginning of drainage not included (after Stegmann & Zeitz 2001).

In other cases, subsidence is visible on the foundations of buildings, which are exposed by the disappearance of the peat (Colour picture 3). Progressing subsidence enforces a regular deepening of the drainage infrastructure, which leads to ever increasing drainage costs. Kuntze (1984) coined this process 'the vicious cycle of peatland utilisation' (Figure 2.6). When the costs of drainage exceed the revenues from agriculture, land use is usually stopped and the peatlands are completely abandoned. If subsidence has been severe, the stopping of the drainage pumps may even lead to the formation of shallow water bodies on those former agricultural fields.

The formation of stagnating soil layers creates a soil profile that contains two water levels. Near the surface, the soil is waterlogged, then a second groundwater level is situated significantly deeper and, in between both waterlogged horizons, a well-aerated soil horizon is located (Zeitz et al. 1987, Colour picture 4). Soil density measurements in fen peatlands have shown that surface waterlogging is caused by a plate-like soil structure that develops on a depth of approximately

Box 2.1: Consequences of drainage for the productivity of tropical peatlands in Southeast Asia

René Dommain

The conventional cultivation of plants in tropical peatlands requires a lowering of the groundwater table to 25–100 cm below the surface (Ambak & Melling 2000). Oil palm and acacia plantations need rather low groundwater levels of 50–80 cm (Hooijer et al. 2012). In smallholder plantations, water levels may even be 1m below ground level as they lack sophisticated adjustable drainage systems. Agricultural use of nutrient-poor acidic raised bogs with a pH of 3–4 requires regular liming and fertilisation (Andriesse 1988, Ambak & Melling 2000), which accelerates peat mineralisation. Furthermore, the application of liquid manure and mineral based nitrogen fertiliser results in extremely high nitrous oxide emissions of 3–40 g N_2O m^{-2} a^{-1} = 10–120 t CO_2e ha^{-1} a^{-1} (Takakai et al. 2006). Despite high fertilisation, yields of many crops such as rice remain lower than on mineral soils and even decrease the longer is the land cultivated (Limin et al. 2007).

The biggest problem of cultivated tropical peatlands is subsidence (Couwenberg et al. 2010, Couwenberg & Hooijer 2013). Subsidence can amount to more than 1 m during the first year after drainage as a result of consolidation (Den Haan et al. 2012, Chapter 2.2.1). After this initial phase, shrinkage and peat oxidation cause further subsidence. In peatlands that are deeply drained for the cultivation of oil palm, peat oxidation causes subsidence of about 5 cm per year (Couwenberg et al. 2010, Couwenberg & Hooijer 2013, Hooijer et al. 2012, Jauhiainen et al. 2012). A common problem in drained oil palm plantations is therefore the exposure of the palm roots, resulting in loss of stability up to the point that the trees fall over. The reason for this is that during the typical operating time of an oil palm plantation of 25 years, more than 1 m of peat can disappear (Hooijer et al. 2012).

The emissions that result from oxidative peat mineralisation are about 10 t CO_2 $ha^{-1}a^{-1}$ at a drainage depth of 10 cm and rise linearly with increasing drainage depth (Couwenberg et al. 2010, Hooijer et al. 2012). A typical drainage depth of -70 cm in oil palm and acacia plantations causes annual GHG emissions of 70 t CO_2 ha^{-1} a^{-1} (Hooijer et al. 2012, Couwenberg & Hooijer 2013). The continuous peat loss may lead to the complete disappearance of the peat. In coastal peatlands, this process can lead to the exposure of acid sulphate soils, which are useless for agriculture. The enormous peat subsidence in coastal tidal areas results in regular flooding with salt or brackish water, which can reach up to 70 km inland and drastically impacts on crop cultivation (Silvius et al. 1984). In order to avoid coastal flooding, tide-steered drainage systems have to be installed. Continuing peat losses require establishing polder systems, which will cause extremely high pumping costs because of the heavy tropical rainfall of more than 2000 mm per year. Under these conditions and for the background of globally rising sea water levels, it is to be expected that large areas of the Indonesian and Malaysian coastal peatlands will literally drown in the near future.

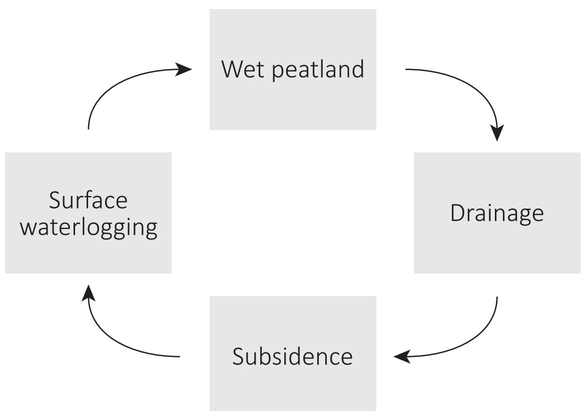


Figure 2.6: Vicious cycle of peatland utilisation (after Kuntze 1984).

30 cm. It is assumed that heavy agricultural machinery, translocation of soil particles and freezing play a role in the formation of this impervious soil layer (Zeitz et al. 1987). This layer is also the reason that capillary groundwater no longer reaches the top soil layer and plants wilt more quickly. Grassroots cannot or hardly penetrate this compacted layer. Consequently, they grow only parallel to the layer and cannot utilise space and nutrients of the soil layers below. It may be expected that, with climate change, the frequency and intensity of heavy precipitation events during summer will increase. Impounded water in summer will cause die off of the sward, resulting in subsequent problems such as wind erosion (Table 2.2). This risk increases further if the crumbled top soil degrades into a very fine dusty, grainy ‘mulm’ substance that is very difficult to wet.

Especially in Eastern Europe, Southeast Asia and Africa, soil productivity of deeply drained and strongly desiccated peatlands is strongly reduced by peat fires (Colour picture 5). After months of smouldering, the fires leave a bare peat that is largely water repellent and hardly wettable. The reclamation of these burned peatland areas for the reestablishment of soil productivity requires highly sophisticated technical input, as well as large financial expenditure. Additionally, peat fires cause enormous greenhouse gas emissions and produce haze most of the year, which poses a serious health risk to the people in the region because of its toxic fumes and fine dust particles.

2.3.2 Management problems resulting from peatland drainage

The load-bearing capacity of peat soils increases initially with drainage as a result of a higher density of the peat, which allows the use of heavy agricultural machinery. Through progressing secondary pedogenesis and the formation of granulose (mulmified) horizons in the topsoil, load-bearing capacity and accessibility decline again (Colour picture 6). The causes for this development are complex and are influenced by several factors (Table 2.2).

The altered physical soil properties reduce water supply to the crops, specially during the summer months. In contrast to pristine mires, seasonal differences in water availability are no longer balanced out via negative feedback mechanisms. Due to drainage, the pore volume is reduced and an oscillation of the peat body is no longer possible. The capillary rise of groundwater is restricted by the above mentioned impermeable soil layers and the hydrophobia of the peat. As the degree of subsidence varies, a microrelief develops on the land, which in combination with the hydrophobic character of the grainy peat leads to a strongly fluctuating moisture content of the top soil (Zeitz 2001). After heavy rainfall, a fine-scale pattern of alternating waterlogged, shallowly inundated, as well as drier spots, forms (Colour picture 4). Periodical water shortages and inundation after heavy rainfall cause that parts of the sod die off. As the bare peat heats up much more than the vegetation covered soil, extreme temperature fluctuations prevent the regrowth of vegetation. The patchy sod reduces the trafficability due to the decreased mechanical support of the grass sod and the grainy, strongly earthified significantly less firm structure of the underlying peat.

2.3.3 Productivity of drained peatlands

Very limited data exist in literature about grassland yields as a function of the progressing alteration of the physical soil properties of drained fen peatlands. Research on this topic has stopped and former experimental sites have been abandoned. However, field experiments under the climatic conditions of Eastern Germany have shown that agricultural yields depend on drainage depth and the progression of secondary pedogenesis (Schmidt et al. 1981), whereas also peat depth influences yields (Figure 2.7). Yields tend to decline with increasing groundwater depth. Along with secondary pedogenesis, yields initially rise (when the peat is only ‘earthified’, in German ‘Erdniedermoor’), but later they decline when pedogenesis has reached the stage of (German) ‘Mulmniedermoor’. Shallow peatlands – such as the large fen peatlands in the East German valley depressions, experience a much stronger decline in yield than deep peatlands. Additional nitrogen fertilisation has less effect on more deeply drained and more strongly degraded sites.

In the long term, these changing soil properties lead to a decline in fen productivity. Chronologically three phases of grassland use on peatlands can be distinguished:

In the first phase (which lasted until the middle of the 20th century) shallow drainage and nitrogen fertilisation led to a quantitative and qualitative increase in agricultural yields.

During the second phase, new technical innovations, progress in plant breeding and intensive grassland management, in combination with renewed and deeper drainage, resulted in maximum yields and high fodder quality. However, this stage did not last – in Germany it presumably lasted less than 20 years.

The current third phase is characterised by extremely declined yields combined with yield insecurity on the progressively very degraded peatlands. Peat subsidence has often made gravity drainage impossible. In order to continue land use, larger investments in water regulation infrastructure become necessary, including the reconditioning and maintenance of bridges and vehicle crossing points. In polder areas, the necessary deeper drainage would require the permanent operation of pumps, which cannot be financed with current water management fees. Moreover, deeper drainage would cause further peatland subsidence. Considering the predicted sea level rise as a result of global climate change, the continuation of peatland drainage is very counterproductive, in particular with respect to coastal protection in the coastal areas of the Baltic Sea and the North Sea (Trepel 2013). In recent years, the problems associated with drainage based peatland utilisation have come notably into the focus of public discussion, which in Germany led to the adoption of state peatland conservation programmes (Box 2.2).

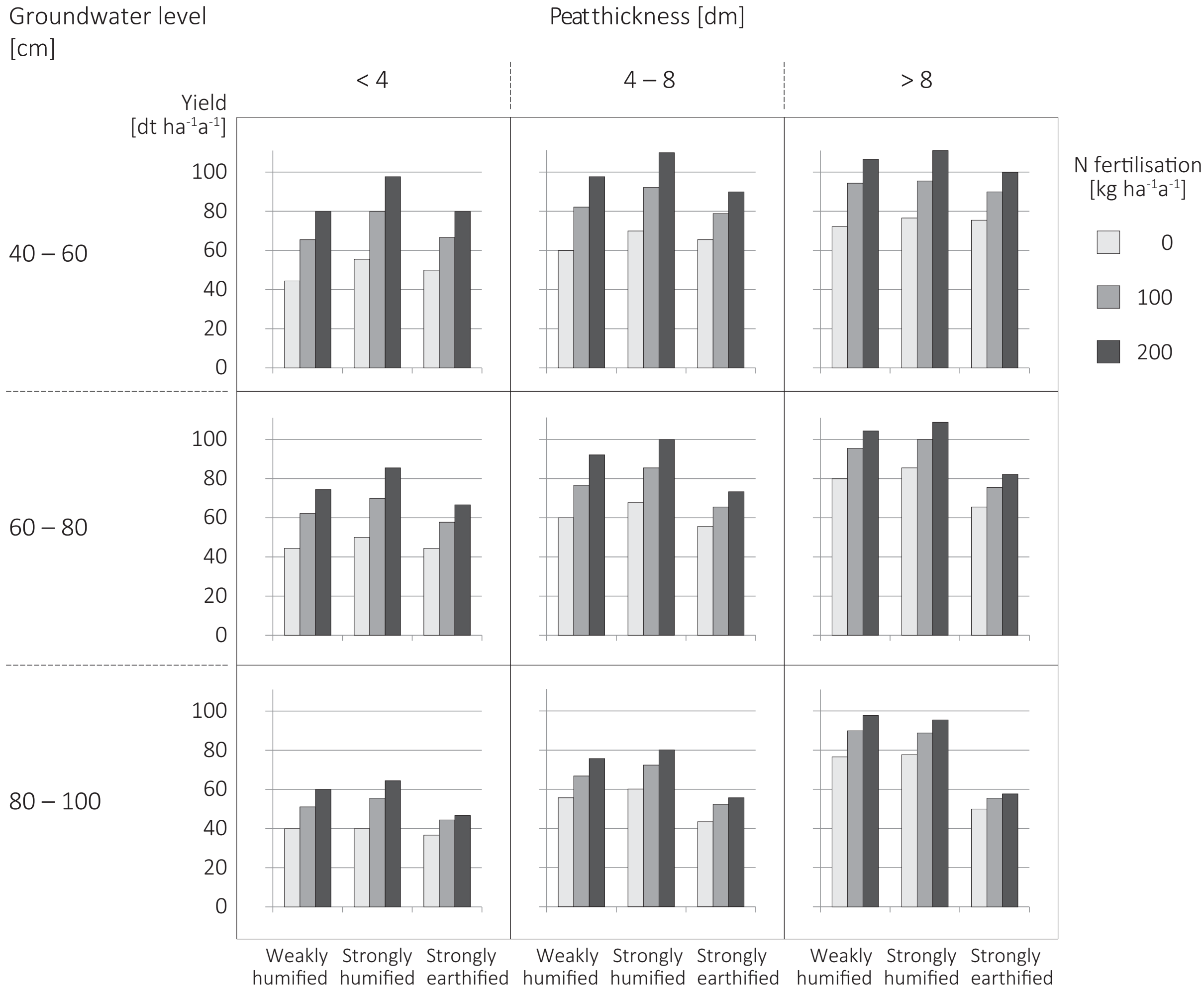


Figure 2.7: Yields of fen grasslands as a function of peat thickness, secondary pedogenesis, groundwater depth and nitrogen fertilisation (after Schmidt et al. 1981).

2.4 Ecosystem services of peatlands

Vera Luthardt & Sabine Wichmann

Awareness about ecosystem services that peatlands provide has grown significantly in recent decades. As semiaquatic ecosystems that mediate between terrestrial and aquatic ecosystems, pristine mires fulfil important functions in the nutrient, carbon and water balance of the landscape. With their specific features, mires furthermore offer refuge to highly specialised species and constitute the last remaining wilderness areas in many parts of the world. The utilisation of peatlands by humans has a large impact on these ecosystem services. Peatlands are drained to optimise provisioning services, which negatively affects many other ecosystem services. By peatland rewetting, part of these ecosystem services can be restored. If rewetting is combined with paludiculture, important regulating services can be restored while maintaining provisioning services of the peatland.

2.4.1 The changing appreciation of peatlands

For many years, mires were avoided as inaccessible wildernesses and wastelands (Chapter 8.1). They only gained importance when they were reclaimed by drainage and were used for agriculture, forestry, fuel peat extraction or as settlement area. The main focus of attention was their production function. As peatlands usability and productivity declined (Chapter 2.3) and knowledge of the ecological functioning of pristine and drained peatlands increased, questions arose about how to deal with peatlands in a sustainable way. Societal priorities widened in the face of biodiversity loss, eutrophication of water bodies and climate change. In

Box 2.2: Peatland conservation in Germany

Simone Witzel

The total area of peatlands including organic soils in Germany is approximately 1.3 million hectare. Some 940,000 ha (68%) are used for agriculture (Röder & Grützmacher 2012). Although peatlands only constitute 6% of the agricultural area, they are responsible for 99% of the CO_2-emissions from all agricultural land (UBA 2013). In total the agricultural peatlands emit 41 megaton of CO_2-e per year, which is 4.3% of the total emissions of Germany (Osterburg et al. 2013).

Due to Germany's federal structure, no coordinated national peatland conservation programme exists; some political declarations have, however, federal relevance. For instance, the national biodiversity strategy (2007) contains aims and objectives with regard to peatland conservation. The responsible authorities of the federal states with the highest peatland coverage (Schleswig-Holstein, Mecklenburg-West Pomerania, Brandenburg, Lower Saxony and Bavaria) released in 2011 a conjoint position on the potentials and the aims for the protection of peatlands and the climate (Jensen et al. 2012). Based on that position, the German Advisory Council on the Environment suggested a federal initiative for peatland conservation in its environmental assessment for 2012 (SRU 2012). All these initiatives aim for the reduction of greenhouse gas emissions, the conservation of biodiversity and the stabilisation of the local and regional hydrological balance. The federal states of Schleswig-Holstein, Mecklenburg-West Pomerania, Brandenburg, Lower Saxony and Bavaria each have their own peatland conservation programmes, which were introduced at different times and have different lifespans (Kowatsch 2007). Lower Saxony adopted its first peatland conservation programme in 1981, whereas Bavaria introduced its peatland development plan in 2005. In Brandenburg, a 10 point plan has been developed as a framework for a peatland conservation plan, similar to that of Mecklenburg-West Pomerania, which was already introduced in 2000 and was updated in 2009. Schleswig-Holstein introduced a programme for the conservation of fens in 2002, which was extended in 2008/09 by including raised bogs. In 2011, the state parliament merged these two programmes into a full peatland conservation programme (Ullrich & Riecken 2012).

The aims and objectives of these programmes are largely similar, but they differ in the degree of importance that is given to specific aims by each of the federal states. For instance, in Mecklenburg-West Pomerania priority is given to the reduction of greenhouse gas emissions. In Schleswig-Holstein, water management plays an important role and the fen programme is closely associated with the ecological improvement of water courses (aiming to support the implementation of the Water Framework Directive, Directive 2000/60/EC; (Chapter 5.4). In Lower Saxony, where the largest areas of raised bogs in Germany occur, peat extraction still takes place over more than 10,000 ha. These areas and their biodiversity are supposed to be largely restored after peat extraction. Recently new priority areas for peat conservation and peatland development are being designated, whereas the programme 'Lower Saxony Mire Landscapes' aims at a far-reaching peatland conservation strategy, which besides bogs, also includes fen peatlands. It also focuses on the reduction of greenhouse gas emissions, the phasing out of peat mining and an adjustment of agricultural use.

Within the peatland conservation programmes, land acquisition and rewetting are generally financially supported. Rewetting measures are implemented in agreement and with consent of the land owners and other stakeholders, who are being compensated financially. The projects are financed by a combination of funds allocated at EU, national, and federal state level or implemented within the framework of a compensation scheme (Intervention and Compensation Regulation, Chapter 7.1). The restored peatland areas are excluded from land use or the targeted water levels are defined in the land charge register. The complementation of peatland conservation with paludiculture is only included in the programme of Mecklenburg-West Pomerania but is discussed for Brandenburg and Lower Saxony as well. In future, paludiculture can contribute to peatland conservation at a larger scale while, at the same time, preserve the production function of peatlands.

Germany and many other countries, the last remaining pristine mires became legally protected and peatland degradation with its complex effects increasingly gained attention.

Since the Millennium Ecosystem Assessment (MEA 2005), efforts are intensifying to consider not only the provisioning services of ecosystems but to take all other 'ancillary' ecosystem services also into account when deciding about land use (Box 2.3). Politics stresses the importance of a transparent presentation and monetary evaluation of ecosystem services (TEEB 2010, EC 2011a), but these requests can only partly be satisfied. Relevant ecosystem services include provisioning, regulating and cultural services (Haines-Young & Potschin 2011), which depend on specific ecosystem functions and processes (Boyd & Banzhaf 2007) and can be assessed by indicators (Schröder et al. 2013). The benefit that stakeholders derive from a peatland process makes that process become a 'service' (Chapter 6.4.1). An example of such functional chain is given in Figure 2.8 for the ecosystem service 'local and regional climate regulation'.

Peatland ecosystem services are more far-reaching than those of other ecosystems, in particular regarding climate regulation. The chain of effects range from the global via the regional level up to the individual farmer or hunter. Qualitative and quantitative assessments of ecosystem services – and possibly also the monetisation and commodification of changes in their provision, are only possible for specific areas and single services . Appropriate methods are currently being developed at both national and international level.

A comprehensive evaluation of peatland ecosystem services requires the assessment of not only all benefits but also of the damage that results from negatively impacted ecosystem functions. The different capacity of natural, drained and rewetted peatlands to provide various ecosystem services is generalised and compared in table Table 2.4 and discussed in detail in the following sections.

2.4.2 Ecosystem services of pristine mires

Pristine mires offer important provisioning services by supplying local people with natural produces, including Cranberries (*Vaccinium oxycoccos*), Cloudberries (*Rubus chamaemorus*), mushrooms, medical plants such as Marsh Labrador Tea (*Ledum palustre*) or Bogbean (*Menyanthes trifoliata*), as well as fodder, litter, and construction materials (Joosten & Clarke 2002). Furthermore, mires provide substantial regulating and cultural services. They have a stabilising effect on local hydrology, attenuate the effects of peak discharge during flooding events, and exert a cooling effect on local climate through evaporation and cloud formation during heat waves and drought periods. An anaerobic environment combined with the filtering characteristics of the peat body results in the conversion of soluble nutrients and pollutants (denitrification) and/or the sequestration of substances in the peat, thereby removing them from the nutrient or carbon cycle (Joosten & Clarke 2002). These functions promote high water quality of adjacent lakes and rivers and thus the supply of drinking water. Continuous peat formation leads not

Box 2.3: Ecosystem services of peatlands

Hans Joosten

In many cases, the utilisation of peatlands leads to irreversible destruction of the ecosystem. Therefore, we distinguish between peat-conserving services that are compatible with the formation and preservation of peat, and peat-consuming services, which eventually destroy the prime feature of peatlands: the presence of peat. Table 2.3 presents an overview of peatland ecosystem goods and services that builds on the Common International Standard for Ecosystem Services (CICES, Haines-Young & Potschin 2011). Unlike CICES, which does not include the supply of subterranean goods such as coal or crude oil in its classification, we consider the supply of peat as an (unsustainable) service of peatlands. In contrast to fossil coal and crude oil, which bear no functional relationship to the covering ecosystems, peat is a functional and defining part of the peatland ecosystem. Like wood in a forest, peat originates within the peatland ecosystem and contributes to its self-organisation and self-regulation. Whereas coal forms by a chemical process that merely requires specific physical conditions (high temperature and pressure) and proceeds in the absence of life, peat formation is a biological process, which is bound to the peatland ecosystem.

The supply of space is nowadays a further distinctive feature of peatlands. Most peatlands are difficult to access and not inhabitable, which makes them in many countries the last spaces unoccupied by humans. Therefore, peatlands often fall victim to the expansion of infrastructure. The common occurrence of peatlands in valleys and on wind-exposed places predestines them for the installation of water reservoirs or wind farms. The value of peatlands in providing these services does not derive from their characteristics as peatlands but from the parallel demands on the characteristics of the landscape.

Table 2.3: Peatland ecosystem goods and services (cf. Joosten & Clarke 2002) according to the Common International Standard for Ecosystem Services (CICES, Haines-Young & Potschin 2011).

Section	Division		Group	Subgroup	Examples of goods and services provided by peatlands	
					(Potentially) peat sequestering (undrained)	**Peat degrading (drained or deeply flooded)**
Provi-sioning services	Nutrition: Food and fodder		Natural		Wild game and fowl, fish, berries, mushrooms, sago, honey	
			Supported	Managed game	Meat of reindeer, deer or ptarmigan	Idem from high density populations that degrade peat by trampling, overgrazing or fire management
				In situ fodder	Fodder for livestock grazing wet peatlands (e.g. Water Buffalo)	Fodder for livestock grazing drained peatlands (e.g. high productivity dairy cattle)
				Ex situ fodder	Hay and silage from wet fen plant material	Hay and silage from drained and fertilised peatland
			Cultivated		Oil from *Shorea*-species, starch from sago	Carrots, potatoes, palm oil, maize and so on
	Water		Drinking, irrigation, industrial and cooling water		Outflowing (surplus) water	Withdrawn surface and groundwater
	Materials	Medicine and delicacy	Pharmaceuticals		Medicinal plants (and animals) e.g. *Drosera*, *Menyanthes*, *Ledum*	Humic preparations, peat baths and poultices, peat based fungi- and bactericides, active coal from peat
			Flavours		Plants for flavouring drinks (e.g. *Menyanthes*, *Acorus*, *Hierochloe*)	Peat for flavouring whiskey
		Fibres	Construction materials		Plants (z.B. *Phragmites*, *Typha*) for thatching, insulation, building, wattling and veneer	Peat as foundation, building and insulation material; wood from drained peatland
			Clothing and textiles		Fur, leather, wool	Cottongrass peat fibre, hemp, wool from high intensity sheep grazing
			Pulp for paper and cellulose		Biomass from *Phragmites*, *Phalaris*, *Papyrus, Typha*	Wood from *Pinus*, *Picea*, *Acacia*
			Absorption, filter and bedding materials		Litter from biomass	Peat for litter in stables, filters, active coal, oil spill absorbent, diapers
			Growing media, potting soils		Peatmoss biomass, biomass compost	Peat as constituent of horticultural growing media
		Fertilisers	Nutrient enrichment		Compost of fen biomass	Peat ash as potassium fertiliser, fen peat as nitrogen fertiliser
			Improvement of soil structure		Biomass compost	Peat for improving soil structure
		Chemicals	Raw materials for chemistry		Refined plant sap, latex (jelutung)	Peat waxes and dyes, active coal made from peat

Section	Division	Group	Subgroup	Examples of goods and services provided by peatlands	
				(Potentially) peat sequestering (undrained)	Peat degrading (drained or deeply flooded)
Provi-sioning services (cont.)	Fuel	Fossil fuel		Marsh gas (methane)	Peat and peat-derived fuels
		Biomass based fuel		Reed, sedges, wood	Palm oil, maize for biogas production, wood, sugar cane for alcohol production
	Space	… for biomass provision		(See nutrition, materials and fuel)	(See nutrition, materials and fuel); fish ponds
		... for urban, industrial and infrastructural development		Space for some wind farms, some transport infra-structure	Space for settlements, harbours, airports, industry com-plexes, hydro-electricity reservoirs, landfills
		… for defence and isolation		Space for low intensity military training grounds	Space for high intensity military training grounds
				Little managed defence and border lines	Intensively managed defence and border lines
				Space for prisons and labour camps	Associated peatland drainage and reclamation
Regulating services	Regulation of waste	Bioremediation		Denitrification, nutrient retention and sequestration in plants and peat	Wastewater treatment, intensive denitrification
		Dilution and sedimentation tation		Clean water supply to dilute downstream pollution, filtering out of pollutants	-
	Regulation of flows	Regulation of water flow		Attenuation of run-off and discharge rates, mitigation of downstream floods	
				Maintenance of base flow, coastal protection	Rapid discharge and increased buffer capacity after drainage
		Regulation of mass flow		Erosion control	
	Regulation of the physi-cal environment	Global climate		Carbon sequestration and storage in peat	Idem in biomass and litter in some boreal peatland forests (temporarily)
		Local and regional climate		Evapotranspiration cooling	
		Water quality		Nutrient retention, denitrification	Waste treatment, denitrification
		Soil conditions		Peat accumulation, initiation and conservation of permafrost	Improved soil structure through secondary pedogen-esis, conservation of permafrost
	Regulation of the biotic environment	Life cycle maintenance and habitat protection		Pollination, seed dispersal	
				Wildfire control	
		Pest and disease control		Control of pathogens and invasive species	
		Gene pool protection		Rare and specialised mire and wetland species	Rare species of (slightly) drained fen meadows

Section	Division	Group	Subgroup	Examples of goods and services provided by peatlands	
				(Potentially) peat sequestering (undrained)	Peat degrading (drained or deeply flooded)
Cultural services	Symbolic	Aesthetic appreciation and inspiration		Areas of Outstanding Natural Beauty, mire patterning	Use of peat and fossil bog wood for artisan objects
				Themes for arts and literature	
		Heritage		Tradition, history and notions of cultural continuity, sense of place	Traditional peat extraction and land use, sense of place
		Symbols and mascots		Hunting trophies, Canadian beaver and Japanese crane as national symbols	
		Reflection and spiritual / religious enrichment		Wilderness, naturalness, quietness, solitude	Wide open spaces, wide horizon
				Notions of ecological and evolutionary connectedness, timelessness and naturalness	Sense of control over the landscape
				Sacred places and species	
	Intellectual and experiential	Recreation and community activities	Recreation and stress mitigation	Tranquility and scenery for tourism and outdoor activities, opportunity for hunting/angling and wildlife watching	
			Social amenity	Employment and volunteering in mire conservation and research	Employment in peat extraction and processing and in drainage-based agriculture and forestry
		Information and knowledge	Cognition and satisfaction of curiosity	Stratigraphical archives (palaeo record, preservation of archaeological artefacts)	
				Extreme habitat conditions and special adaptations of mire organisms, (reference for) self organisation – and regulation	Cultural land use history and sociology, behaviour of disturbed systems
			Indication	Palaeoecological record, indicator organisms	
			Education	Subject matter for educational literature, field excursions, presentations	Idem with respect to peat extraction, agriculture, forestry, water management and road building
	Transformation	Character development		Options for development of new tastes, moral and social skills, and growing awareness of evolutionary and ecological connectedness	
	Option and bequest	Continuous provision of ecosystem services		Benefits that still have to be discovered	Benefits that still have to be discovered

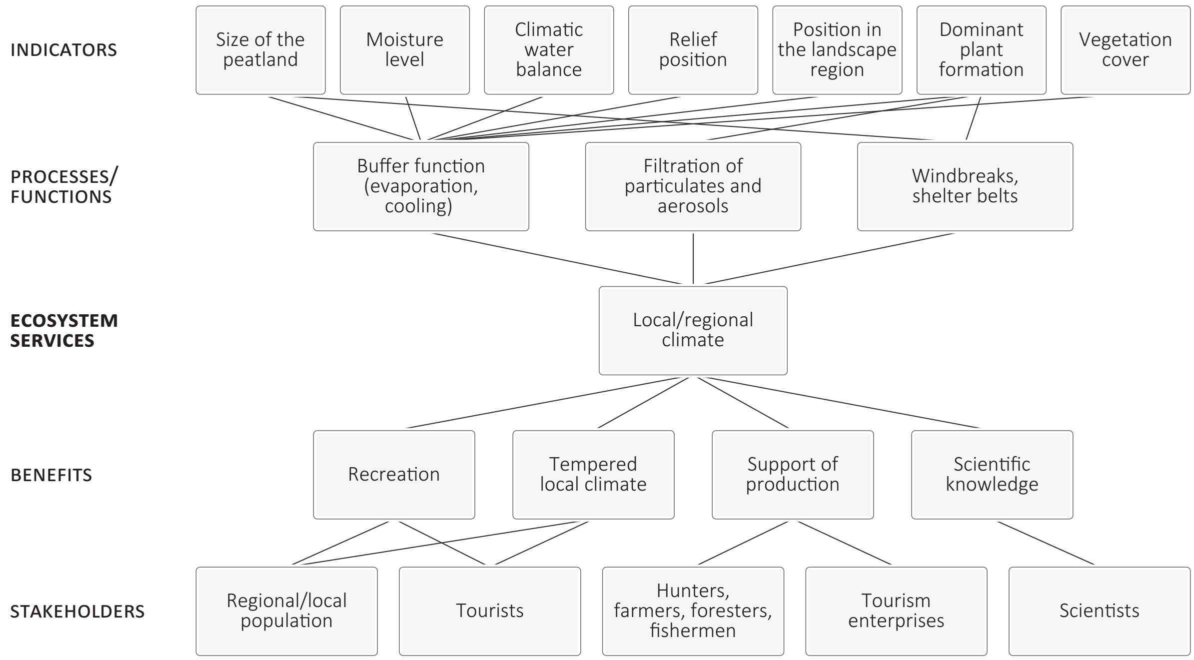


Figure 2.8: Factors determining the performance of the peatland ecosystem service 'regulation of the local/regional climate' (after Schröder et al. 2013).

only to the sequestration of carbon and mineral components of plants but also to the production of a raw material.

Mires are habitats with very specific characteristics such as excess water availability, a cool and moist microclimate and a continuously upward growing surface, whereas some mire types are extremely nutrient poor and acidic. They can only be populated by organisms that are adapted to these extreme conditions. In the course of time, very special biotic communities have developed in mires that with their food webs, flow paths of matter and energy and other interrelations represent particularly valuable ecosystems. Thus, a considerable part of biodiversity is found in these special habitats, even when they cover only a small area of the landscape (Luthardt & Zeitz 2014).

In these ecosystems, which often have a history of development that may exceed 10,000 years, natural process dynamics – both of the present and of the past, can be observed and studied. As places of wilderness, mires play a prominent role in science, as well as for recreation, experiencing nature, inspiration and environmental education.

2.4.3 The change of ecosystem services by drainage

Up until now, peatlands had to be drained in order to generate provisioning services. Drainage induces a wide range of processes (Chapter 2.2 and 2.3) and particularly affects the regulating services of peatlands: Peat accumulation stops and irreversible peat degradation sets in, nutrients sequestered in the peat are released, the hydrological balance is severely disturbed, and the habitats of specialised mire organisms disappear to make place for those of more ordinary species. Carbon sinks turn into sources that very rapidly release considerable amounts of carbon and other substances that had been sequestered over a very long time span. The filter and buffer function is dramatically reduced.

In Northern Germany, productive use of drained peatlands is largely directed at fodder production, peat extraction, and recently also at the production of biomass for energy generation. The landscape does not differ any more from that of other terrestrial areas, so that the special ambiance of mires can no longer be experienced. Instead, accessibility and cultural components start to characterize the landscape. Only the open space with its wide horizon remains. Science has to redirect its research focus on conversion processes, the behaviour of disturbed systems and succession.

Table 2.4: Selected ecosystem services of peatlands in dependence of water management and utilisation (Positive impact: +++= strong, ++= medium, += existing; negative impact: ---= strong, --= medium, -= existing; 0= no influence: ~= changing over time).

Section	Group	Pristine/ near natural	Drained with land use	Drained & abandoned	Rewetted & unused	Paludiculture
Provisioning services	Food and fodder	+	+++	0	0	++
	Plant fibres (building material, litter, substrate)	+	++	0	0	++
	Biomass fuel	0	++	0	0	++
Regulating services	Climate regulation (global & local)	++	---	---	+++	+++
	Water purification/ nutrient retention	++	---	---	+~	++~
	Regulation of the water cycle	+++	---	---	++	++
	Habitat for specialised species/gene pool	+++	+	--	++~	++~
Cultural services	Experience of nature, recreation	+++	+	+	++	+
	Information and knowledge (processes, archive)	+++	+	+	++	++

Regional value creation used to be positive over long time as it was based on local resources. However, the growing inputs of material and energy that drainage demands make the balance increasingly negative. Eventually, conventional drainage based generation of provisioning services on peatlands is a cul-de-sac (Chapter 2.3).

2.4.4 Ecosystem services of rewetted peatlands

The rewetting of degraded peatlands focuses in particular on the re-establishment of mire typical biodiversity, on the improvement of water quality, on the reduction of greenhouse gas emissions and on the restoration of other regulating services. Some of these aims can be achieved almost instantly; other functions may take an extended time span to fully recover. Rewetting also secures cultural services by preserving the peat layer as an archive of climate, landscape and cultural history. Up until now, however, rewetting of peatlands largely implied the renouncement of the production capacity of peatlands.

Paludiculture is the only form of land use that allows using the provisioning capacity of peatlands without substantially compromising the supply of regulating or cultural services. In comparison to drained peatlands the latter services improve considerably (Table 2.4, Chapter 5).