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Restoring peatlands in European landscapes

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1 Introduction

A survey in the EU (European Environmental Agency 2020) showed that the conservation status of protected sites belonging to the habitat category 'Bogs, Mires and fens' is most frequently assessed as 'bad' (50%). Less than 10% is considered of 'good conservation status'. Even worse, when compared to the previous survey in 2012, more than 50% of the wetlands that already had a status of 'unfavourable' or 'bad' have continued to deteriorate. The main reasons for this negative trend are agricultural activities, land-use conversion and drainage.

Wetlands are '*areas that are inundated or saturated by water for all or part of the year to the extent that it supports soil microbes and rooted plants adapted for life in saturated soil conditions*' (Joosten 2016). Wet conditions lead to low oxygen availability in the soil and result in incomplete decomposition of dead plant material. If the water table remains sufficiently high and stable throughout the year, organic material accumulates. Organic wetland soils are called *peat*

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when the soil organic matter content is higher than 30% and the thickness of the organic layer exceeds 30 cm (Joosten et al. 2017).

The present chapter focuses on peatlands in temperate Europe. First we describe undisturbed lowland peatlands and the services they provide, which we compare to progressively degraded systems. Especially in north-western Europe, human population density and land-use intensity are so high that many of the once ubiquitous peatlands have disappeared or have severely degraded. For example, in Flanders, in the north of Belgium, approximately 95% of the peatlands that were still present in 1950 were drained for agriculture and did not survive into the twenty-first century (Decleer et al. 2016). For other European countries, estimated peatland losses for that same time period range from 60% to 84% (European Commission 2007). At the same time, we know that already in 1950, most peatlands had been lost completely due to drainage or peat-cutting in earlier periods (Leenders 1989). Exact numbers from the period before 1950 are not available but it seems reasonable to assume that north-western Europe has lost almost all of its peatlands. In less densely populated regions, for example in Northern Europe, most peatlands have been drained for forestry. For Europe as a whole, it is estimated that approximately 75 000 km^2 has completely disappeared, 275 000 km^2 has been drained and 320 000 km^2 is still in a natural or near-natural state (Joosten et al. 2017). The large majority of the latter are nowadays found in Russia, while undisturbed peatlands in the rest of Europe only cover a fraction of their past surface. Consequently, there is a huge need not only to conserve the few remaining peatlands but also to restore degraded ones, especially because they deliver important ecosystem services.

2 Ecosystem services of peatlands

Several studies (e.g. Bonn et al. 2016; Decleer et al. 2016) have shown that undisturbed peatlands deliver at least 15–17 of the services that are distinguished in the Common International Classification of Ecosystem Services CICES (EU 2014, 2016). These can be grouped into services to water flow, water purification, carbon cycling and biodiversity.

2.1 Services to water flow

Undrained peatlands dampen the effects of sudden precipitation peaks on the surface water system, as intact peat soil expands ('swells') under conditions of high water availability, thereby creating additional storage room. This process is called 'mire breathing' (Ingram 1982; Nijp et al. 2019). Water flow to the surface water system is further reduced by the topography of these peatlands, characterised by an intricated pattern of alternating hummocks, tussocks and hollows (Price et al. 2016). However, this service is often over-estimated, mainly because the peatlands' storage capacity for additional water is limited because peatlands are – by definition – water saturated. Also, the hydraulic permeability of most peatlands is low, meaning that they cannot release sufficient amounts of water to sustain the base flow in dry periods.

2.2 Services to water purification

Natural peatlands contain large amounts of nutrients, especially nitrogen (N). It is estimated that Boreal peatlands of the Northern hemisphere alone contain 8–15 Gt of N (Limpens et al. 2006). Like all green plants, peatland plants need nutrients, especially nitrogen. This implies that C-sequestration in peatlands automatically leads to N-sequestration as well. The flooded zones with highly productive tall sedges and reeds particularly serve as nutrient sinks, not in the least because they also trap sediments and the nutrients therein (Olde Venterink et al. 2002; Fisher and Acreman 2004).

2.3 Services to carbon cycling

According to present estimates, peatlands store globally at least 650 Gt of C on approximately 3% of the terrestrial surface. This equates to more than 20% of the global total organic C stock (Yu 2011, 2012; Scharlemann et al. 2014; Leifeld and Menichetti 2018). As such, they hold the most C per unit area of any terrestrial ecosystem (Zomer et al. 2016; Griscom et al. 2017). Globally restoring all drained peatlands, as well as preventing pristine peatlands from degradation, would result in the capture of almost 2 Pg CO_2 eq. per year. This is approximately 7% of the mitigation needed to keep global warming below 2°C (Griscom et al. 2017).

2.4 Services to biodiversity

The peatland environment is rather hostile to most organisms. Low soil oxygen levels, low redox potential and high concentrations of dissolved compounds such as NH_4^+, HS^-, Fe^{2+} and sometimes Al^{3+} are toxic to many biota. Therefore, most peatlands are home to true specialist species that are adapted and restricted to this extreme environment. Because of the current global scarcity of undisturbed peatlands, these species have often become rare and/or endangered. Some species of sedges (e.g. *Carex limosa, C. chordorrhiza*) and mosses (e.g. *Tomentypnum nitens, Paludella squarrosa*) are currently only found in undisturbed peatlands. The biodiversity value of undrained peatlands is therefore high, certainly in Europe (Hájek et al. 2006).

3 Types of peatland

Peatlands are highly diverse and complex systems due to large differences in the supporting hydrology. Various peatland classification systems have been developed, but unfortunately they are often incompatible. In the present chapter, we therefore restrict ourselves to a rather simple but useful classification (Du Rietz 1954):

- *Bogs* occur where precipitation is the primary source of water. Rainwater is mineral-poor and hardly buffered against acidification, while the dominant plants in bogs, peat mosses of the genus *Sphagnum*, excrete protons. Bogs are always acidic.
- *Fens*, on the other hand, are also fed by upwelling groundwater. Depending on the flow path, this groundwater can be relatively poor to extremely rich in dissolved minerals (Pietsch 1976; Shotyk 1988; Hajkova et al. 2004; Kharanzhevskaya et al. 2020). If the water has percolated through geological substrata with soluble minerals, water can be saturated with minerals. Important soil minerals are Ca^{2+} compounds, especially $CaCO_3$ and $CaSO_4$, but other minerals can also be found. If, on the other hand, the groundwater has travelled only short distances or through mineral-poor substrata, its composition is more similar to that of rainwater.
- A third major peatland type is *floodplains* that lie along streams or rivers and are, as the name suggests, strongly affected by regular flooding with surface water. Depending on its origin, surface water can vary largely in chemical composition, ranging from almost rainwater-like to extremely mineral rich. In densely populated areas, surface water is typically also loaded with nutrients and pollutants.

4 Characteristics of undisturbed peatlands

4.1. Water dynamics

Different peatland types are supplied with water from different origin. This not only affects water chemical composition but also the water regime (= pattern in water level fluctuations) and with that the dynamics of water saturation in the top peat layer (Wierda et al. 1997; Barber et al. 2004; Ahmad et al. 2021). Water level fluctuations in rainwater-fed systems depend on the variation of rainfall and evapotranspiration over the year. *Bogs* are normally found in areas with a significant precipitation surplus and a rainfall pattern that is more or less evenly distributed over the year, so that fluctuations in water levels are rather small. Fluctuation patterns in *fens* depend on the origin of the water. Upwelling groundwater that originates from deep soil layers often leads to very stable water levels because its main source is usually a large infiltration area, and water can take decades to reach the surface of the fen. Groundwater from shallow layers usually stems from smaller and nearby situated infiltration areas, with larger fluctuations in water levels as a result. Water levels in surface water-fed systems are generally very dynamic. *Floodplains* therefore typically exhibit the least stable water levels of all wetland types. This is certainly the case today: drainage systems have been optimised to maximise the export of excess water to the surface water system, resulting in large discharge peaks (Hirt et al. 2011).

4.2 Water chemistry

Water chemistry and water regime both exert a primary influence on soil conditions and nutrient availability. Firstly, the water itself may transport nutrients (N, P, K) to the site. This is typically the case with surface water that is naturally more nutrient-rich than rain- and groundwater. Under natural conditions, the latter two are generally more nutrient-poor. Moreover, internal nutrient release by peat decomposition is normally very low in fens and bogs due to the stable water levels and anaerobic conditions, making aerobic decomposition near impossible. This is much less the case in floodplains with more dynamic water levels or in sites where upwelling groundwater originates from small infiltration systems. Under such conditions oxygen can at least temporarily penetrate into the soil with decomposition rates that are not negligible. Here the release of nutrients from decomposing organic material may contribute significantly to nutrient loading.

4.3 Vegetation zonation

There is large variation in local topography, nutrient availability, water type and soil water saturation within one and the same peatland system. A comparison between vegetation zonation in undisturbed lowland peatlands (Wassen et al. 1996; Schipper et al. 2007) and the distribution of plant remnants in soils of now disturbed peatlands (van Diggelen et al. 1991) shows that a zonation in vegetation is very typical within lowland peatlands (Fig. 1). Along the edges, i.e. where the wetland borders the mineral soil, water supply fluctuates throughout the year and the water regime is rather dynamic. Here, nutrient availability is moderately high and this zone is typically covered by riparian alder forest. The second zone is fed by the upwelling of nutrient-poor groundwater from deeper layers, leading to very stable water levels and low vascular vegetation biomass. The vegetation is very open and is dominated by ‘brown mosses’ (e.g. from the *Amblystegiaceae* family) and small sedges (*Carex* sp.). The groundwater impact diminishes closer to the river and flooding intensity increases, leading to larger water table fluctuations and higher nutrient availability. Consequently,

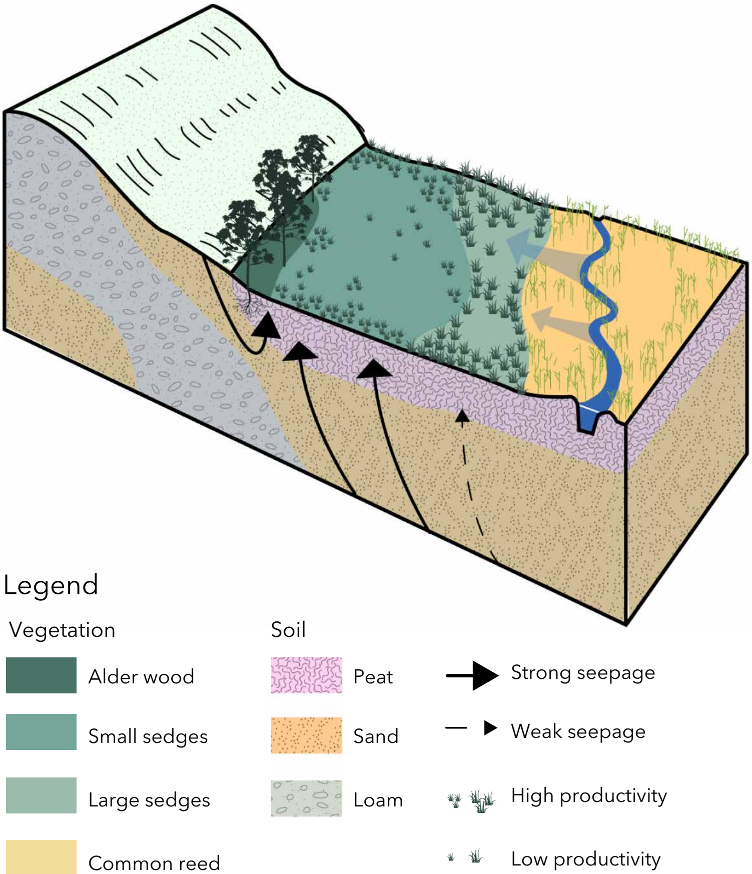

Figure 1 Typical vegetation zonation in an undisturbed riverine lowland peatland. The arrows indicate major water flows.

the vegetation is more productive there. The first zone is dominated by large sedges (*Carex* sp.), closer to the river these sedges are replaced by reed (*Phragmites australis*) and under very nutrient-rich conditions even by cattail (*Typha* sp.).

5 Effects of land-use changes on peatlands

5.1 Changes outside peatlands

5.1.1 Changes in the groundwater system

Increasing human interferences at the landscape scale have resulted in hydrological changes that directly and indirectly affect peatlands. A massive intervention is drainage, which often takes place at the level of the entire catchment. Drainage causes a reduction in groundwater recharge rates of the aquifer, lowers groundwater potential and subsequently reduces upward groundwater discharge into the peatland. In regions with a high precipitation surplus, such as western Europe, a decreased upward groundwater flow is generally replaced by infiltrating rainwater which leads to the acidification of the topsoil (Wassen et al. 1996; van Diggelen et al. 2006; Grootjans et al. 2006). Furthermore, local drainage of adjacent fields and groundwater abstraction also alters groundwater flows and lowers discharge rates (van Diggelen et al. 1994).

5.1.2 Changes in the surface water system

The majority of surface water systems have also been anthropogenically modified. Rivers have been straightened and embanked to prevent flooding, with large effects on hydrological conditions inside adjacent peatlands. Soil erosion and peak discharge of surface water started to increase in the Middle Ages because of the large-scale clearcutting of forests. In the peatlands adjacent to these rivers, this led to greatly enhanced deposition of mineral sediments (Notebaert et al. 2011).

5.1.3 Land-use intensification around the peatlands

Nowadays the remaining peatlands are typically situated in agricultural landscapes where they receive a large input of nutrients, pesticides and other pollutants via groundwater and surface water. Peatlands connected to an infiltration area that is intensively used by agriculture are typically subject to eutrophication. Often, however, increased nutrient availability is also the result of so-called internal eutrophication. This is caused by complex hydrogeochemical processes that are triggered by an altered chemical composition of groundwater (Hartog et al. 2004; Lamers et al. 2002; Smolders et al. 2010; Cirkel et al. 2014, see Box 1).

5.1.4 Air pollution

More recently, air pollution with sulphur and nitrogen further contributed to the eutrophication of peatlands (Robertson et al. 1989; Dise et al. 2009). Although atmospheric sulphur deposition strongly decreased due to measures taken by industry, nitrogen deposition is still very high in western Europe (European Environmental Agency 2022).

Box 1: Chemical processes in heavily fertilised landscapes

In western Europe, most groundwater-fed fens are hydrologically connected to infiltration areas that are covered by intensively used agricultural fields. This has consequences for the chemical composition of the infiltrating water, which is enriched with nitrate NO_3^- and sulphate SO_4^{2-}. Redox processes (Table 1) along the flow paths of groundwater (Fig. 2) further modify water chemistry, thus affecting hydrochemical conditions inside the peatlands wherever this water wells up.

Nitrate in the infiltrating water is usually removed through conversion to N_2 gas via redox reactions with pyrite (FeS_2) and reactive organic matter (reactions R1 to R3). Full oxidation of pyrite by nitrate (reaction R3) produces H^+, which in its turn leads to increased calcium and magnesium concentrations through dissolution of carbonates (reaction R6) and cation exchange processes (reaction R7). Depending on the specific groundwater flow paths and spatial geochemical variation, groundwater originating from agricultural infiltration areas is either nitrate-rich, nitrate + sulphate-rich or sulphate-rich. The combination of high concentrations with a high groundwater flux can lead to staggeringly high loads of nitrate (up to 1500 kg N/ha/year) and sulphate (up to 3000 kg S/ha/year) in discharge areas (Aggenbach et al. 2020). When such groundwater enters anaerobic organic soil layers, nitrate and sulphate are reduced via the reactions R1 and R4. This causes anaerobic decomposition of organic matter and thus losses of accumulated carbon from the peatland. These losses can be so high that in some peatlands the C-budget has changed from C-accumulation to C-release. The concomitant production of alkalinity elevates the pH and promotes decomposition processes inside the peatland. As a result, organically bound N and P are released. In a situation with high sulphate levels, in the absence of nitrate, sulphides precipitate with iron. This lowers the iron hydroxide pool in the soil and causes mobilisation of phosphate adsorbed to iron hydroxides. All reactions described previously lead to an increase in internal eutrophication.

Iron sulphides accumulate under waterlogged conditions but a strong drop in groundwater levels, for example in dry summers, causes aeration of the soil and oxidation of these sulphides. This leads to strong acidification by reaction R5 and causes leaching of calcium (reactions R6 and R7). Fens that are affected by the input of sulphate-rich groundwater are vulnerable to acidification, especially when the buildup of the acidification capacity exceeds the acid buffer capacity of the peat. When the peat is iron poor, a high sulphate load leads to high sulphide concentrations (HS^- and S^{2-}) in the porewater. High concentrations of sulphides are toxic to many plant species.

Table 1 Relevant chemical processes in heavily fertilised landscapes.

Reaction	Location	Chemical reaction
		Nitrate reduction
R1	2, 3, 5	by anaerobic decomposition: $4\ NO_3^- + 5\ CH_2O \rightarrow 2\ N_2\uparrow + CO_2 + 4\ HCO_3^- + 3\ H_2O$
R2	2, 3	by facultative pyrite oxidation: $5\ FeS_2 + 14\ NO_3^- + 4\ H^+ \rightarrow 7\ N_2\uparrow + 5\ Fe^{2+} + 10\ SO_4^{2-} + 2\ H_2O$
R3	2, 3	by full pyrite oxidation: $10\ FeS_2 + 30\ NO_3^- + 20\ H_2O \rightarrow 10\ Fe(OH)_3 + 15\ N_2\uparrow + 20\ SO_4^{2-} + 10\ H^+$
		Sulphate reduction
R4	2, 3, 5	by anaerobic decomposition: $2\ SO_4^{2-} + 3.5\ CH_2O + Fe^{2+} \rightarrow FeS_2 + 2\ HCO_3^- + 1.5\ CO_2 + 2.5\ H_2O$
		Pyrite oxidation
R5	5	by oxygen: $FeS_2 + 3.75\ O_2 + 3.5\ H_2O \rightarrow Fe(OH)_3 + 2\ SO_4^{2-} + 4\ H^+$
		Effects of acidification
R6	5	on carbonate dilution: $Ca_xMg_{(1-x)}CO_3 + 2\ H^+ \leftrightarrow x\ Ca^{2+} + (1-x)\ Mg^{2+} + CO_2 + H_2O$
R7	5	on cation exchange: $x\ H^+ + x\ Kat\text{-}CEC \rightarrow x\ Kat^+ + x\ H\text{-}CEC$

Numbers for locations refer to Fig. 2.

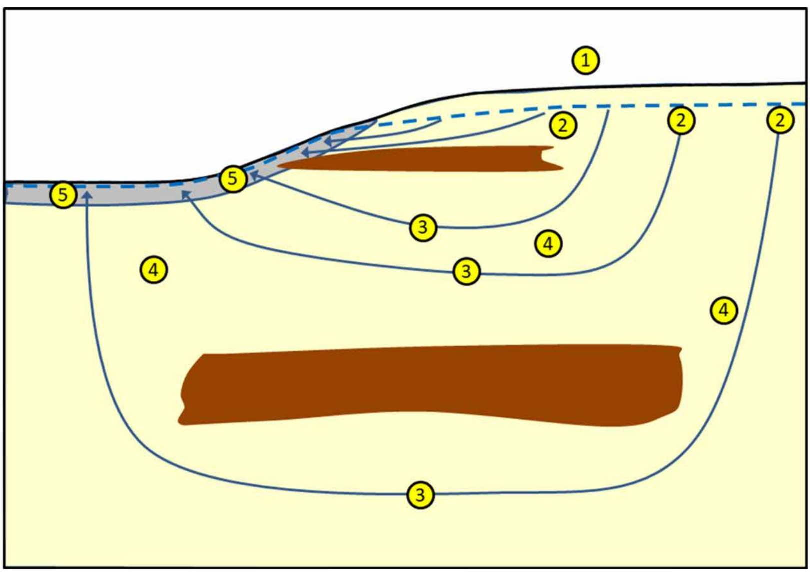

Figure 2 Cross section with important chemical processes along groundwater flow paths from infiltration area to discharge area in the peatland. Colors: yellow = aquifer, brown = aquitard, grey = peat; blue line = groundwater flow path; blue dotted line = groundwater level.

5.2 Changes inside peatlands

5.2.1 Peat extraction

A very drastic and irreversible change for peatlands is peat ('turf') extraction. In Europe, most peat extraction took place during the thirteenth to nineteenth century. Here, peat provided energy for the expanding cities (Unger 1984; Deforce et al. 2007; Jongepier et al. 2011). Most peat was extracted from bogs as bog turf has a higher carbon content than fen turf. This resulted in the complete loss of large bog complexes throughout Europe and with them the intermingled fen systems (Leenders 1989). Peat extraction for fuel was less common in brook valleys with fens, where extraction was often only a local phenomenon. Here, peat extraction deeper than the groundwater levels resulted in small pools, where peat growth started anew in the form of floating fens (van Diggelen et al. 1996). Yet many of these ponds, especially those in valleys, were kept open and used for fish farming or for hunting (Burny 1999). Due to these practices, large areas of fen habitat have been converted into pond systems.

5.2.2 Drainage of peatlands for agriculture

The most common land-use change inside peatlands is drainage for agriculture. In the past, many fens were converted into hay meadows by drainage. The drier conditions increased productivity and growth of edible grasses for livestock. Before the introduction of artificial fertilisers, conventional management normally consisted of haymaking at the end of summer. Centuries of hay removal without adding fertiliser depleted nutrients to the extent that low productive fen meadows developed, often with a very species-rich vegetation of 30–40 vascular plant species/m^2 (Klötzli 1978; Jansen et al. 2000). From the end of the nineteenth century onwards, fertilisation and drainage intensity started to increase substantially (Succow and Joosten 2012). This led to the development of species poor-grasslands with often less than 5 species/m^2, dominated by competitive grassland species (van Diggelen et al. 2005). In the last decades of the twentieth century, further intensification of drainage even enabled tillage and conversion to arable corn or potato fields.

5.2.3 Establishment of peatland nature reserves

Vast and undisturbed peatlands no longer exist in the densely populated areas of Europe. Instead, only small and isolated remnants persist, mainly within nature protection areas (see Box 2). They lost many of their characteristic species while most of the remaining species are endangered Red List species (IUCN 2021). Recolonisation by typical plant species is unlikely because these have a short-lived seed bank (Klimkowska et al. 2010) and dispersion is low or absent because the distance to source populations is too large (Ozinga et al. 2009).

Box 2. Case study of landscape changes in the Demer valley (Belgium) and future challenges for the conservation of its remaining peatlands

The peatlands of the Demer valley are a prime example of remnant peatlands in an agricultural landscape. Human impact here started in the Roman era when large-scale deforestation of the upstream catchment altered patterns of sedimentation (Notebaert et al. 2011; Verstraeten et al. 2018). This covered peat layers close to the river with alluvial deposits. Alluvial sedimentation expanded in the Middle Ages by digging canals to direct silt-laden river water over the peatlands as natural fertiliser. Inundation was also promoted by peat extraction in bogs upstream, thus reducing the capacity for water retention there. Furthermore, fens downstream were also subject to peat extraction, especially in the eighteenth and nineteenth centuries, lasting until the interbellum (Vervoort and Deneef, 1996). In the twentieth century, the river catchment underwent even more drastic changes. Large-scale industrial and household pollution in the 1960s and 1970s accelerated the straightening of the Demer that had started in the eighteenth century. This was done to remove the polluted water as fast as possible, causing a drop in groundwater and surface water levels. Cut-off meanders were subsequently used as landfills, converted into fishing ponds or levelled to be used for agriculture. Due to the drop in water levels, agriculture in the form of arable fields, particularly corn, was made possible. This subsequently replaced many of the traditional hay meadows. Areas that remained too wet were primarily planted with poplars. In addition, some of the peatlands were drained and built up as industrial area or also used as landfill up until the 1980s (Fig. 3a).

Despite these drastic changes, some small peatlands persisted. They were taken into nature management from the late 1970s onwards. Since then, restoration actions such as the removal of poplar plantations have managed to revive species such as *Carex diandra* (Fig. 3d). Furthermore, they are home to some of the last remaining populations of rare peatland mosses in the Northwest European lowlands such as *Hamatocaulis vernicosus*, *Philonotis marchica* and *Sphagnum affine*. Yet, the long-term persistence of these remnant peatlands faces many challenges on different scales. At a microscale, nature management is increasingly subject to mechanisation causing soil compaction and preventing the formation of the microtopography necessary for peat growth. At a mesoscale, the extant drainage network continues to cause peat oxidation. Furthermore these drainage networks act as 'inundation highways', spreading external surface water laden with pollutants from sewage and with nutrients and runoff from adjacent agriculture (Fig. 3b). This is exacerbated at a macroscale by urbanisation, expansion of arable fields and climate change. Urbanisation and agricultural expansion decrease water infiltration and cause faster run-off upstream, worsening inundation of the downstream peatlands. They also increase groundwater use, deplete aquifers and lower groundwater discharge. Climate change causes an increasing number of extreme events such as droughts (e.g. 2018, 2019, 2022) and long inundations (e.g. 1998, 2016, 2021). Consequently, several Red list species are now constricted to a limited number of buoyant patches on former peat excavation sites. The buoyancy prevents inundation during flooding and allows for waterlogged conditions during drought (Fig. 3c).

It is clear that the conservation of the last remaining peatlands of the Demer will require a multilevel approach that combines concerted efforts of all stakeholders, including nature and water managers, farmers and municipalities. At the micro level, nature management should take care not to compact soil and promote micro-topography for new peat growth. This will allow carbon and nutrient sequestration, on the one hand, and water retention in drought spells on the other. However, it will require more investment in skilled manual labourers working with adapted equipment. To halt peat oxidation and stimulate new peat growth, it will also be necessary to block drainage canals to allow for year-round water logging. At the meso-level, sufficient hydrological isolation is required to prevent inundation with surface water containing sewage and agricultural runoff. This will necessitate careful landscape planning as soil subsistence due to historical peat degradation has caused these peatlands to become among the lowest parts of the floodplain. Because the floodplain also serves as a water retention area to prevent inundation of urbanised areas, flood management will need to differentiate between alluvial areas and peatlands. Currently, peatland vegetation is limited to floating fens that float on open water bodies that go up and down with water table fluctuations (Arcadis Belgium, 2016). However, floating fens only comprise a few hundred square meters with limited room for expansion (Fig. 3b) Therefore, it is impossible to attain sustainable populations of endangered species here. Finally, at the watershed level, it is essential to continue water purification, protect peatland-feeding aquifers by limiting groundwater extraction and, importantly, to improve upstream water retention in urbanised and agricultural areas to reduce downstream flooding.

Only now the surface area under nature management has become large enough to start with the first two prerequisites: changing the internal management and blocking the drainage canals. Inundation prevention is not yet built into current landscape planning schemes. Flood protection of surviving peatlands will need to be put at a similar level as flood protection of urbanised areas. This remains an urgent task of water managers and municipalities. A similar challenge remains for mitigating water pollution and groundwater extraction. This requires that farmers and municipalities reduce agricultural and household use of water and prevent agricultural runoff and sewage discharge. Finally, upstream municipalities and farmers will need to adopt urban planning schemes and agricultural strategies to maximise local water retention. These management schemes, properly integrated, will ultimately benefit all ecosystem service goals, including adaptation to climate change.

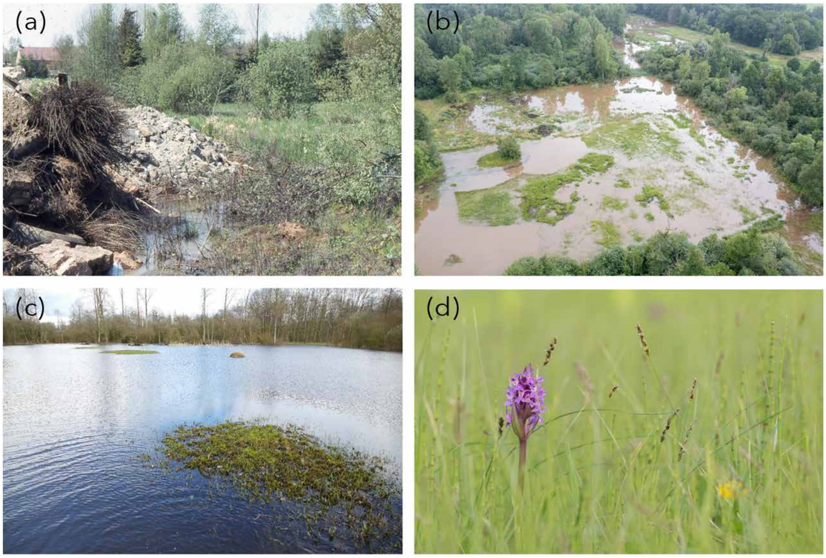

Figure 3 (a) Remnant peatland, formerly with the endangered *Eriophorum gracile*, used as a landfill in 1982. (b) Flooding of a peatland in 2021 with brown-coloured silt-laden water characteristic of agricultural runoff. Patches with floating fens (fresh green color) escape inundation. (c) Small floating fens during natural flooding with local, non-polluted surface and groundwater. Notice the difference in water colour with (b). (d) Vegetation of the floating fens with red listed species *Carex diandra* and *Dactylorhiza majalis*. Photographs Luc Vervoort (a, c) and Kevin Feytons (b, d; https://www.kevinfeytons.be/).

5.3 Land-use legacies

Water table drawdown and concomitant peat oxidation triggers a myriad of cascading effects that alter peat properties. First, soil meso- and macrofauna such as earthworms find their way into the desiccated peat, where they fragment large particles of organic matter (Wu et al., 2017). Second, microbial community composition changes, which correlates with elevated activity of enzymes such as phenol oxidase (Fenner et al. 2005). Subsequent soil alterations can be rapid and include loss of organic matter as CO_2 or as dissolved organic carbon (DOC), soil subsidence, soil acidification, increase in bulk density, loss of hydraulic conductivity and decrease in water storage capacity (Zeitz and Velty 2002; Laiho 2006; Leifeld et al. 2011; Erkens et al. 2016; Liu et al. 2022). Drainage also leads to changes in the topography. Whereas the slope of the soil surface is usually small in undrained fens (Schipper et al. 2007; Succow and Joosten 2012), uneven subsidence leads to locally steep slopes in drained peatlands (Aggenbach et al. 2021). As a result of these processes, water table fluctuations are larger in drained peatlands (Price and Schlotzhauer 1999) thus enhancing further soil degradation. In addition, changes in peat quality and molecular composition take place in a sequential manner: easily degradable fractions of the peat such as cellulose are the first to be consumed upon oxidation, resulting in a relative accumulation of more recalcitrant material such as lignin (Emsens et al. 2020).

Drainage and subsequent increased decomposition rates trigger eutrophication by mobilisation of inorganic compounds from the organic soil (Lamers et al. 2015). This is evidenced by the concentration and accumulation of minerals and macronutrients such as ammonium (NH_4^+) followed by nitrate (NO_3^-), sulphates (SO_4^{2-}) or phosphates (PO_4^{3-}) in soil and pore water. Once large quantities of nutrients have been mobilised from the peat, this process cannot simply be reversed by peat rewetting. In fact, rewetting may even further enhance nutrient availability, particularly of phosphates, due to anaerobic reduction and desorption processes (Emsens et al. 2016; Zak and Gelbrecht 2007).

Encroachment of competitive vascular plants occurs at the expense of smaller and inherently slower-growing fen specialist species (Kotowski and van Diggelen 2004), which can no longer compete for light and consequently perish (Fig. 4). As a rule of thumb, light competition in fen communities of small sedges and brown mosses starts to become significant when less than 30% of the incoming solar radiation is able to reach the soil surface (Emsens et al. 2018).

The abovementioned profound shifts in peatland characteristics, functioning and resilience are not easily reversible within – at least – a decadal time span. This is why we refer to them as a 'land-use legacy' or 'degradation

Figure 4 Eutrophication leads to the encroachment of productive plant species such as reed (*Phragmites australis*) at the expense of slow-growing peatland specialists. Picture from the 'Zegge' in Belgium; a remnant peatland reserve that is completely surrounded and heavily affected by intensive agriculture (© KMDA/Jonas Verhulst.).

legacy'. Loss of soil carbon and soil structure due to drainage and degradation, for example, leads to profound changes in landscape topography (Fig. 5) and may remain clearly visible in the landscape for decades or centuries to come. Degradation legacies pose significant constraints on the restoration prospects of a peatland (Emsens et al. 2021). Tackling them always requires a combination of in situ restoration measures as well as measures that target the hydrology of the groundwater and surface water systems influencing the former peatland.

6 Restoration targets

The globally accepted definition of restoration says *Ecological restoration* is *the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed. It aims to move a degraded ecosystem*

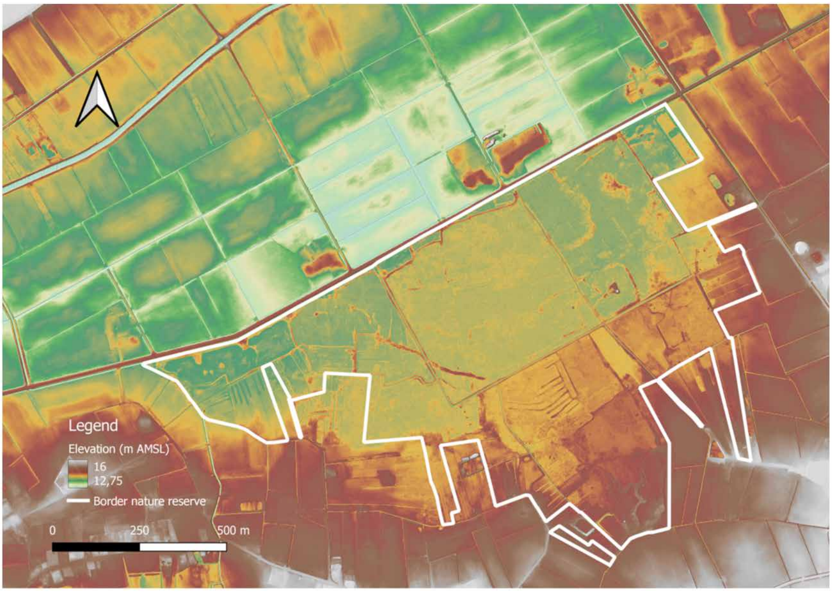

Figure 5 Elevation map of the peatland nature reserve 'De Zegge', Belgium, and its surroundings, showing clear signs of land-use legacies. Prior to large-scale land conversion and drainage, the area north of the reserve lay at approximately the same height as 'De Zegge'. In the beginning of the 1950s, however, the peatlands north of the reserve were drained and converted into agricultural land. This led to a soil subsidence of over 1 m and estimated losses of 31 ton CO_2/ha/year until all the peat there was gone. The groundwater that used to feed the reserve now drains directly into the subsided agricultural lands, causing ongoing soil desiccation, eutrophication and acidification within the borders of the reserve. Background: Digital Terrain Model (horizontal resolution: 1 m, vertical resolution: 1 cm).© Digitaal Vlaanderen

to a trajectory of recovery that allows adaptation to local and global changes, as well as persistence and evolution of its component species (Gann et al. 2019). What this definition does not elaborate on is where this recovery should lead to and what the final target should be. Harms et al. (1993) and Swart et al. (2001) depict several alternative targets to pursue, depending on the initial condition of the damaged ecosystem and the intended use of the restored system.

6.1 Natural target

Many people interpret restoration as a process that enables a return to a natural system that is, as much as possible, identical to the pre-degradation situation. The aim of such natural target is to restore a so-called *wilderness* landscape, in this case, peatlands that are identical to those under natural conditions. However, as discussed previously, long-term land-use legacies have irreversibly altered soil conditions and water flows. In such situations, restoration typically leads to a situation that differs considerably from the undisturbed one (Kreyling et al. 2021). Moreover, a complete return to a natural situation is often not wanted. A wilderness target for peatland restoration requires the restoration of large-scale hydrological systems and allows only very limited human activity inside the restored area. In other words, such a target requires a lot of space and is only feasible in sparsely populated areas.

6.2 Semi-natural target

An alternative target is the restoration of a *semi-natural* or *arcadian* landscape where the ecological conditions are modified by human activities but are still mainly determined by natural gradients. However, these gradients are typically no longer large-scale but instead split up in smaller, more local ones. Human impact on the landscape is larger and management activities are essential to keep the landscape in a certain state. The aforementioned fen meadows are a typical example of such semi-natural systems. They came into being after the superficial drainage of peatlands that were used for haymaking. Mowing is essential to keep these meadows open, but productivity is too low for modern farming standards. Their high biodiversity value can be preserved only with additional subsidies for nature conservation or landscape protection.

6.3 Functional target

A third target consists of the restoration of now degraded peatlands into a productive *functional* landscape in which intensive agricultural land use is combined with the preservation of important ecosystem services related to carbon cycling, hydrology and nutrients. This implies that fertilisers and pesticides are applied very sparingly and do not pollute groundwater or surface water. Tillage is avoided to prevent excess damage to the peat soils. The sites are not drained to avoid (further) carbon loss but are rewetted instead, with water tables that stay near the soil surface throughout the year. Instead of present-day 'classical' agriculture, the cultivation of 'new' crops needs to be developed. A promising initiative is what is called 'paludiculture' or wet agriculture (Wichtmann et al. 2016; Tanneberger et al. 2021), although most of the 'new' practices are in fact centuries old. Examples include the cultivation of crops like Cattail (*Typha*) for insulation material, reed (*Phragmites*) for thatching or the production of cellulose, willows (*Salix*) for cellulose or fuel pellets, or peat mosses (*Sphagnum*) for potting soil (Mulholland et al. 2020). In February 2023, an increasing number of paludiculture experiments is being carried out in countries like Germany, Poland, the Netherlands, the UK and Ireland and grant schemes to develop commercially viable paludiculture on lowland peat soils are starting to appear. The big challenge here is to develop cultivation types that yield enough income to live from but do not require so much fertilisation that there is a high risk of water pollution by nutrient runoff.

7 The way forward

Whatever restoration target is chosen, rewetting is a crucial first step to stop further degradation (Evans et al. 2021). At the same time not all rewetting is equal. The hydrochemical composition of the water and the rewetting technique applied strongly determine which targets can be achieved. A sudden rewetting by deep inundation with surface water generally leads to strong internal eutrophication and often also leads to high methane emissions (Zak and McInnes 2022). This option therefore hampers the achievement of more demanding restoration targets. On the other hand, 'slow' rewetting, i.e. gradually increasing water levels, preferably with unpolluted groundwater, leaves more options open and is therefore, wherever possible, always the preferred choice .

A wilderness restoration target has the most stringent requirements with respect to stability of water levels and hydrochemical conditions and will normally not be easy to attain in densely populated regions. However, where possible, this target should be the highest priority because it delivers most ecosystem services (Table 2). Wherever this target is pursued, the first requirement is to restore the natural hydrology. As long as water levels are not suitable for peat formation, it makes no sense to stop former management in order to rewild a drained peatland. Unsuitable hydrological conditions do not favour the development of a carbon-accumulating peatlands but instead promote the encroachment of eutrophic shrubs and bushes of low

Table 2 Ecosystem services delivered by different restoration targets

Ecosystem service	Wilderness	Semi-natural	Wet agriculture	Drained peatlands
Regulation of water flow and water purification	++	++	++	--
Carbon sequestration	++	-	0/+?	--
Biodiversity	++	++	0/-	-
Agricultural profits	--	0/+	+	++

++: highly positive effect; +: positive effect; 0: negligible effect; -: negative effect; --: highly negative effect. After van Diggelen and Verdonschot (2021).

conservation value (Opdekamp et al. 2012). Even when the hydrological system has been restored, prospects are not very hopeful in sites with a large degradation legacy. The wilderness target thus seems most appropriate for less disturbed landscapes. Human use of rewilded areas is limited and consists mainly of low-intensity tourism and possibly some hunting and fishing. Agriculture is not an option.

The target 'semi-natural restoration' has less strict requirements and is more easily achievable in landscapes where former land use has left its legacy. Contrary to the wilderness target, the semi-natural target does not necessarily require a conversion of the whole landscape, provided the activities around the site do not affect the hydrological conditions or nutrient levels within the site (Grootjans et al. 2006). In practice, this implies cessation of fertilisation anywhere near the peatland, as well as cessation of excessive fertilisation in or near infiltration areas and streams that feed the peatland. In addition, all drainage and groundwater abstraction in the vicinity should be halted and the natural morphology of streams restored to reduce the rates of catchment-scale water runoff. Regional canals and ditches should be closed or, if blocking is not possible, water levels should be raised, and the water of heavily eutrophied or polluted streams that flow into the wetland should be purified prior to entering.

In situ restoration measures typically include rewetting by closing drainage ditches, cessation of all direct fertilisation activities, suppression of competitive plants by regular mowing and biomass removal, or even species reintroductions (Lamers et al. 2015). In extreme cases, even the complete removal of a eutrophic and degraded topsoil can be considered, thereby exposing a less disturbed underlying peat layer (Klimkowska et al. 2015). The latter measure is very invasive and expensive, with potentially negative effects on the surrounding landscape and on the short-term carbon footprint (Zak and McInnes 2022). Therefore, it should always be treated with caution or as a last resort. Nonetheless, it may locally result in a complete 'reset' of the degraded topsoil layer, which lowers nutrient levels and may benefit the establishment of peat-forming specialist vegetation (Emsens et al. 2015; Zak et al. 2017).

Human use of semi-natural areas includes agriculture, hunting, fishing and a wide range of tourist activities, such as walking, cycling or – if climate permits – skiing or skating in winter. Agricultural activities are essential to manage the landscape but must be nature-friendly. Consequently, current intensive agriculture is not possible and farmers need an additional income besides agriculture. Recreation can serve as a good alternative. A recent study (Robinson et al. 2022) on the economy of nature revealed that tourists spend between 270 and 450 million Euros/year in the Dutch area of Zuid-Limburg alone, i.e. 6000–10 000 Euros/ha. In reality they spend most of their time in the semi-natural parts of the region, which is ca. 10 000 ha out of 45 000 for the total countryside, suggesting that the income per hectare for that part is even higher.

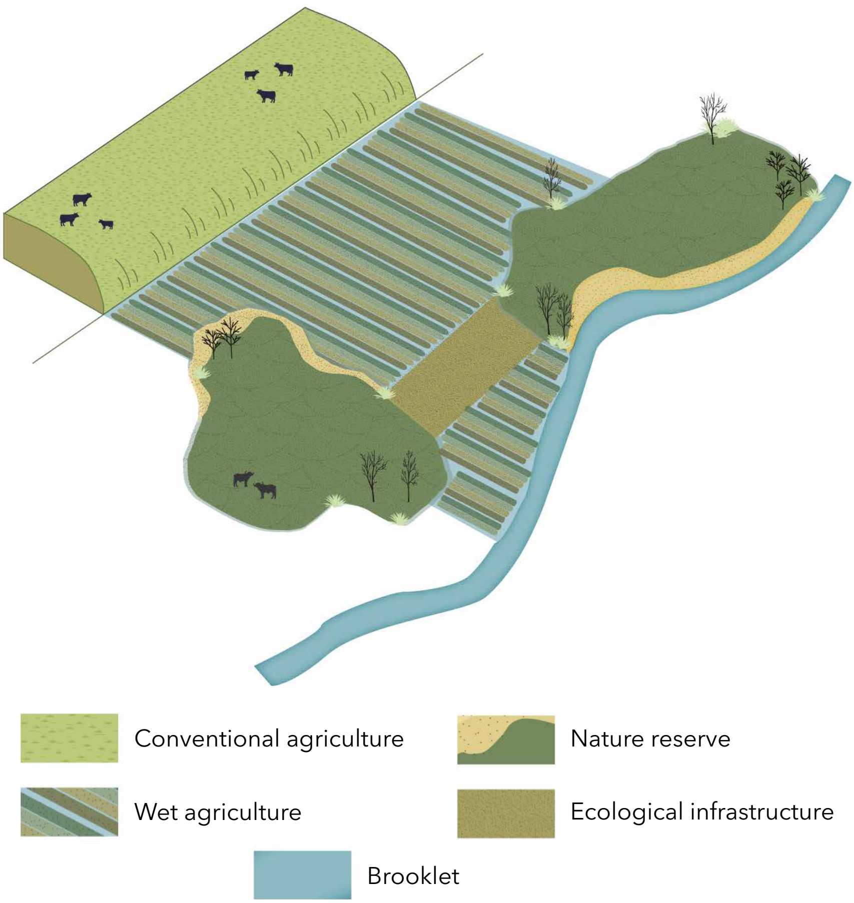

Figure 6 Landscape layout where wet agriculture buffers two nature reserves from influences of intensive land use and at the same time connects them in the form of a Green Infrastucture element.

The target 'wet agriculture' has few abiotic requirements and is perfectly suitable for sites with a persistent land-use legacy. In fact, a soil saturated with nutrients is to some degree beneficial for this type of land use because it increases productivity (Geurts et al. 2020). The only constraint for wet agriculture is that harvest is sustainable, i.e. that water levels are at the surface during the whole year and, depending on the crop, that nutrients are not depleted. At present, this farming technique is still in its infancy. Several crops are being tested and economic models being developed. Once established, this type of land use would be a perfect solution for buffer zones on former agricultural land located between sites with higher biodiversity value and areas of intensive and conventional land use (Fig. 6).

Setting sustainable restoration goals requires unambiguous choices, based on the legacies of the former land use, and physical and social conditions. A pitfall is to retain old land-use practices that hamper the development of feasible restoration targets. Or, worse, not make any choice at all. When clear and explicit choices have been made, peatlands generating multiple ecosystem services can be revived and provide new opportunities for both people and nature.

8 Conclusion and future trends

We distinguish at least two key trends in future research to look out and aim for.

The first trend we see is on the fundamental level: there is an urgent need for integrative and multidisciplinary research that takes into account multiple aspects of wetland functioning and restoration, which can be obtained by combining various scientific disciplines. This is particularly relevant for peatlands, which are highly diverse and complex ecosystems. A solid and profound understanding of key research topics, including ecosystem resilience (in response to change or stressors) or ecosystem restoration trajectories, can only be obtained using such approach. For example, there is a growing trend of combining molecular and soil microbial ecology with soil biogeochemistry, vegetation science and landscape ecology, which may unravel formerly unknown links or feedback loops between relevant actors within an ecosystem. Or, relevant biogeochemical processes that are studied on the local plot scale can be upscaled to the regional scale by GIS extrapolation and remote sensing. At the same time, there is a growing need for large-scale and cross-country studies with proper spatial replication, as extrapolation of data from only one site to the regional scale may produce biased or inaccurate results (Zalman et al. 2018). It is key that researchers with different scientific backgrounds form international consortia to jointly work on a topic or research question in a holistic manner. Multidisciplinary studies that cover a wide spatial gradient are thus likely to increase over the next few decades.

Second, the focus of applied peatland research is gradually moving towards a search for alternative and sustainable forms of land use in which multiple ecosystem services can be restored or conserved. This is relevant for degraded peatlands that are currently still used for conventional agriculture that includes fertilisation, drainage or peat soil tillage. As discussed in this chapter, paludiculture may provide an important part of the solution. Even though the concept of paludiculture is very old, scientific research on paludiculture is just emerging (Wichtmann et al. 2016; Ziegler et al. 2021). In the next few decades, it will therefore be important to initiate (more) large-scale trials on paludiculture and to subsequently investigate all relevant aspects ranging from economic feasibility and production processes to effects on the ecosystem carbon cycle, the water balance and biodiversity.

9 Where to look for further information

The following books provide a good overview of general wetland functioning, including relevant biogeochemical processes:

- Mitsch, W. J. and Gosselink, J. G. 2015. *Wetlands*. John Wiley & Sons, Hoboken.
- Maltby, E. and Barker, T. (Eds) 2009. *The Wetlands Handbook*. Wiley-Blackwell, Oxford.

The following books, journals or papers provide more detailed information specifically on peatlands, including peatland conservation, restoration and paludiculture:

- 'Mires & Peat' journal (http://www.mires-and-peat.net/)
- Wichtmann, W. et al. 2016. *Paludiculture: Productive Use of Wet Peatlands*. Schweizerbart Science Publishers, Stuttgart.
- Succow, M. and Joosten, H. 2012. *Landschaftsökologische Moorkunde* (in German). Schweizerbart Science Publishers, Stuttgart.
- Lamers, L. P. et al. 2015. Ecological restoration of rich fens in Europe and North America: from trial and error to an evidence-based approach. *Biological Reviews* 90(1), 182–203.

Key research and conservation efforts in this area can, amongst others, be found at the following organisations:

- International Mire Conservation Group (IMCG) (http://www.imcg.net/pages/home.php)
- Greifswald Mire Centre (https://greifswaldmoor.de/home.html)
- IUCN UK Peatland Programme (https://www.iucn-uk-peatlandprogramme.org/)

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