Ecological restoration in drained peatlands

– best practices from Finland

Maarit Similä, Kaisu Aapala and Jouni Penttinen (eds)

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ECOLOGICAL RESTORATION IN DRAINED PEATLANDS – BEST PRACTICES FROM FINLAND

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Eight years after restoration. PHOTO: MAARIT SIMILÄ

More than 25 years of experience

A new comprehensive handbook for the restoration of drained peatlands was published in Finnish in July 2013 (Aapala et al. 2013). The handbook was produced with the help of dozens of Finnish peatland experts. It compiles the knowhow accumulated over more than 25 years of peatland habitat restoration in Finland, together with useful background ecological information on peat and the hydrology of peatlands.

The handbook was primarily written on the basis of experiences gained from restoring peatland sites in protected areas. Our aim is to increase awareness of the ecological bases for peatland habitat restoration, and thereby promote effective peatland restoration work both inside protected areas and in areas where commercially forestry is practised. The handbook is intended for everyone involved in the planning and implementation of active restoration measures in peatlands that have been drained to promote forestry.

The production of the handbook was coordinated by the Finnish Expert Group for Peatland Restoration (SuoELO*) in connection with the Boreal Peatland LIFE project and the Forest Biodiversity Programme METSO, with funding from the Ministry of the Environment.

This abridged English-language version of the guidebook summarises the most important contents of the full Finnish version. The publication of the English version was financed through the Boreal Peatland LIFE project. We would like to warmly thank everyone who has contributed to the original handbook and this English summary version.

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*SuoELO is a collaborative working group consisting of experts from several key organisations including Metsähallitus, the Finnish Environment Institute, the Finnish Forest Research Institute, the Forestry Development Centre Tapio, the University of Eastern Finland, the University of Jyväskylä and the Ministry of the Environment. The Finnish Forest Centre joined the working group in 2013.

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Figure 1. *Kurjenrahka National Park contains the most extensive protected peatlands in Southwest Finland.* PHOTO: LENTOKUVA VALLAS.

1 Introduction

Kaisu Aapala and Maarit Similä

In international nature conservation policy contexts the restoration of ecosystems has become an important tool for mitigating biodiversity loss and safeguarding ecosystem services. The European Union's new biodiversity strategy (European Union 2010) and the 10th Conference of Parties to the international Convention on Biological Diversity held in Nagoya in 2010 both highlighted ecological restoration as a key means to halt biodiversity loss and the degradation of ecosystem services by 2020. Finland's own national nature conservation policies also aim to promote active restoration work in protected areas and in commercially managed forests (Valtioneuvosto 2012a, b).

Ecological restoration involves measures designed to help ecosystems that have been impoverished, damaged or destroyed due to human activity to revert to their natural state, or as near to their natural state as possible (Society for Ecological Restoration International Science & Policy Working Group 2004). Natural conditions and ecological processes can be re-established in peatland ecosystems affected by human activity much more rapidly with the help of well-planned restoration measures than by leaving them to return to a near natural state through slow natural processes.

One of the primary objectives of restoration is to improve the quality of species' habitats and biotopes, and thus slow or halt the rate of biodiversity loss.

The advantages of preserving and restoring peatlands with regard to mitigating climate change are also recognised in international climate policy-making. At the Durban climate conference in 2011 it was agreed that parties to the Kyoto Protocol could from 2013 onwards include the benefits of the restoration of wetlands, including peatlands, in their greenhouse gas reporting (COP 17 Durban 2011, Decision 2/CMP7).

Finland originally had natural peatlands with a total area of some 10.4 million hectares (Vasander 1998). Today the country has about 8.7 million ha of peatlands, of which some 4.7 million ha

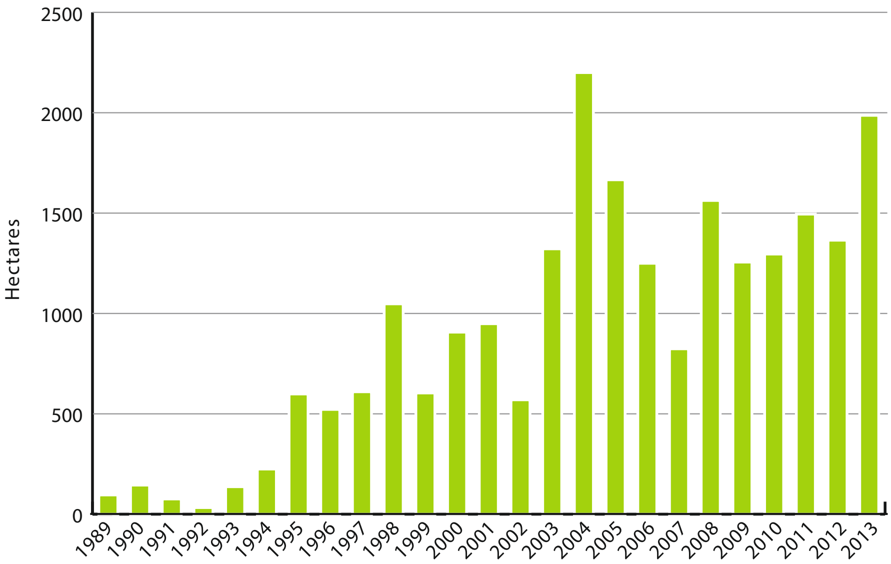
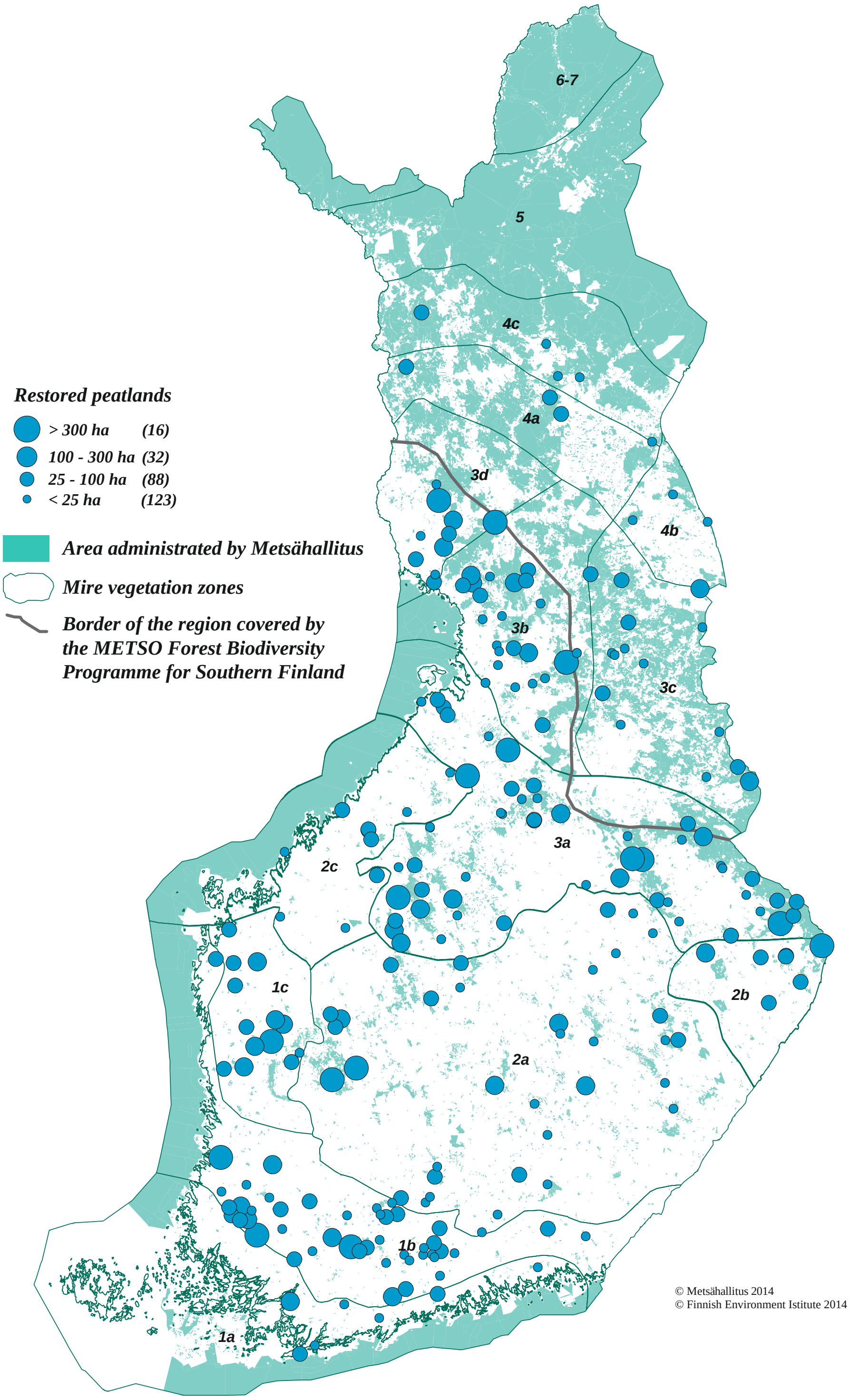


Figure 2. *Areas of peatland restored annually in state-owned protected areas 1989–2013.*

have been artificially drained and about 4 million ha remain undrained (Finnish Forest Research Institute 2013). Some 1.2 million ha of peatland lie within protected areas (Figures 1 and 4), though more than 50,000 ha of this area had been drained before the areas were protected (National peatland strategy working group 2011). During the years 1989–2013 peatlands with a total area of about 20,000 ha were restored (Figures 2 and 3). It has been estimated that ecological peatland restoration would still be needed in a total area of around 17,000 ha in existing state-owned protected areas and in some 1,000 ha in privately owned protected areas (Metsähallitus 2012).

The first peatland restoration trials in Finland were conducted in the 1970s and 1980s in peatland sites of very high ecological value very soon after they had been drained. Initially drainage ditches were blocked manually, but since 1992 peatland restoration work has usually involved machinery. The areas of peatland restored annually increased from the mid-1990s thanks to the availability of EU Life funding (Info box 2). Ecological habitat restoration measures became a more established means of managing protected areas from 2003 when the first national Forest Biodiversity Programme METSO was launched and a habitat restoration working group appointed by the Ministry of the Environment published its findings (Rassi et al. 2003).



← ***Figure 3.*** *Peatlands in protected areas where restoration work had been conducted by the end of 2013. The areas shown as administered by Metsähallitus include both lands and waters. Mire vegetation zones: 1a Plateau bogs, 1b–1c Concentric bogs, 2a–2c Eccentric bogs and Sphagnum fuscum bogs, 3a–3d Sedge aapa mires, 4a–4c Flark aapa mires, 5 Northern aapa mires, 6–7 Palsa mires and orohemiarctic mires.*

INFO BOX 1

METSÄHALLITUS NATURAL HERITAGE SERVICES MANAGES FINLAND'S PROTECTED AREAS

The Finnish State owns about 125,000 square kilometres of land – amounting to about one third of Finland's total land area (Figure 4, page 5). State-owned lands and waters in Finland are administered by Metsähallitus. Metsähallitus's Forestry Business Unit administers commercially managed forests, while Metsähallitus Natural Heritage Services is responsible for the ecological management of protected areas. Natural Heritage Services manages areas totalling 70,000 sq km (39,000 sq km of land and 31,000 sq km of marine and inland waters). In addition to these state-owned protected areas, Metsähallitus Natural Heritage Services also carries out habitat restoration and ecological management work in many privately owned protected areas around Finland.

METSÄHALLITUS

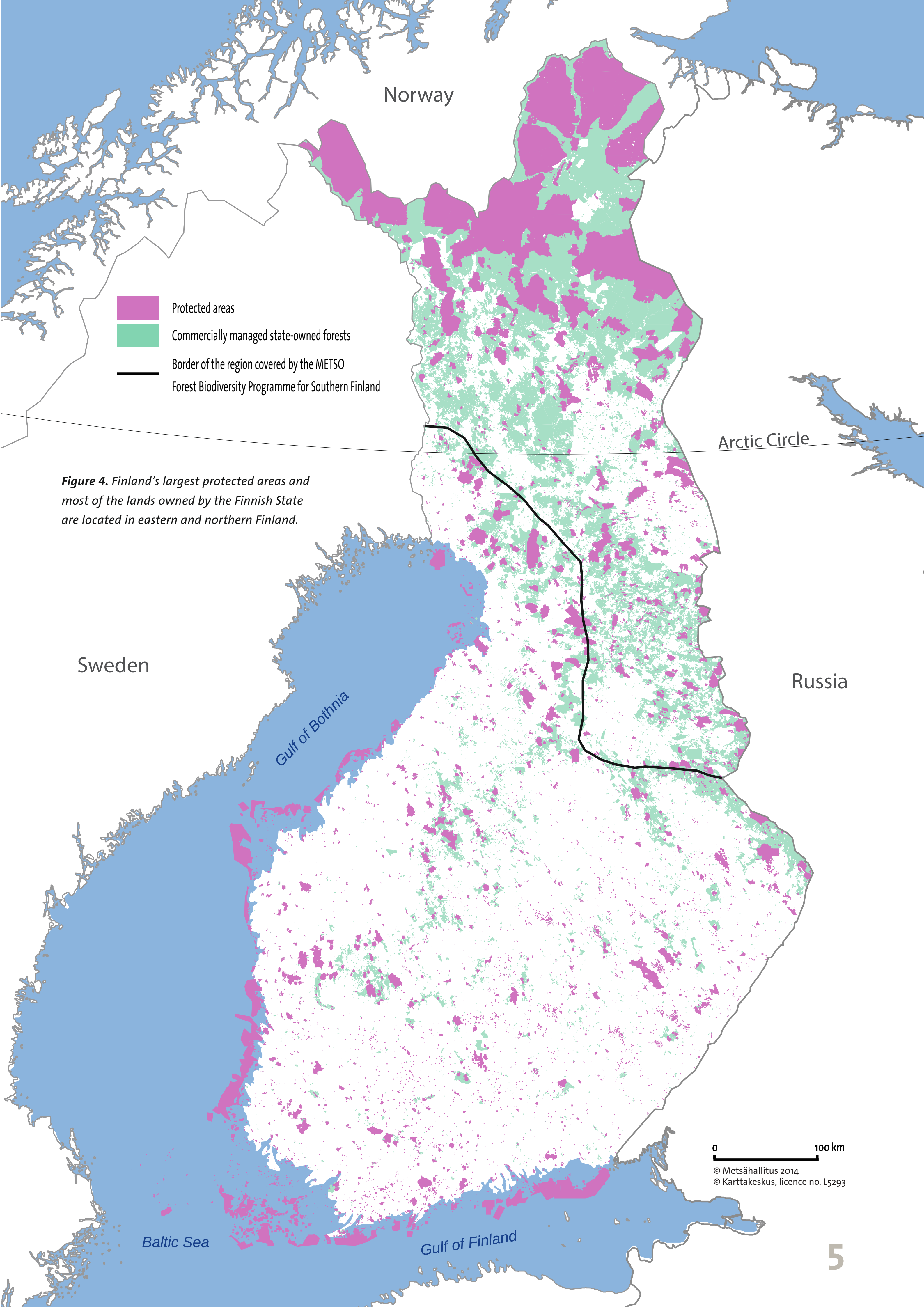


Figure 4. *Finland's largest protected areas and most of the lands owned by the Finnish State are located in eastern and northern Finland.*

EU Life projects and peatland restoration

Mikko Tiira

Peatlands and wetlands in LIFE projects

Many Natura 2000 habitat types are associated with peatlands. Those found in Finland include active raised bogs, aapa mires, bog woodlands, palsa mires and petrifying springs with tufa formation (Cratoneurion). Peatland habitats are the focus of many Life projects in Finland and elsewhere in the EU. By 2012 the European Commission had funded a total of 150 projects related to peatlands across Europe. These projects have promoted the conservation of peatlands through additional protection or enhanced land use planning, by restoring peatlands earlier cleared for agriculture or drained for forestry purposes, and even by recreating areas of peatland habitat where such areas had been lost.

Life projects related to peatlands in Finland

Finland's first Life projects were launched in 1995. By 2012 a total of 124 projects had been concluded or were under way, including about 50 Life Nature projects. Almost half of Finland's Life nature projects have concerned peatlands to a greater or lesser degree. The total budget for projects related to peatland restoration, including still ongoing projects, amounts to more than 40 million euros, about half of which has come from EU funds. By the end of 2012 areas of peatland habitat totalling more than 9,000 hectares had been restored around Finland using Life funding.

Life funding has particularly been used to restore aapa mires, for a total area of more than 4,000 ha. Some 1,700 ha of active and degraded raised bogs have also been restored, as well as just over 2,000 ha of bog woodlands, about 350 ha of alkaline fens, just over 100 ha of transition mires and quaking bogs (in projects focusing on sites valuable for their birdlife). A small number of sites with Fennoscandian springs and spring fens have also been restored.

Life projects related to peatlands elsewhere in the EU

In other northerly countries in the EU Life projects focusing on peatlands have been most numerous in Latvia (about 10). In Sweden there have been 13 projects, but these almost all focused on acquiring peatlands for protection. The project 'Life to ad(d) mire', launched in 2012, is the first Life project in Sweden to focus on peatland restoration.

The types of peatlands targeted by projects around the EU vary greatly. According to the Life projects databank, more than 80 peatland projects have been related to alkaline fens, particularly in Germany and Italy, but also in Belgium, Holland, the Nordic Countries, the Baltic Countries and Britain. Bog woodlands have been protected or restored through almost 80 projects, most widely in Finland and Germany, though Sweden and Latvia also have almost ten projects each targeting bog woodlands. The conservation of transition mires and quaking bogs has been promoted through almost 80 projects, with almost 15 in each of Finland, Germany and Belgium, and elsewhere 10 or fewer. Projects targeting raised bogs are by far the most numerous (over 100). In the British Isles many projects have striven to restore blanket bogs. Projects targeting aapa mires have mainly been realised in Finland, and to a lesser extent Sweden.

All Life projects also involve active publicity work. For example, in Finland's Boreal Peatland Life Project, information about the ecology, protection and restoration of peatlands has been publicised by various means such as a portable mire exhibition with comic strips and nature quizzes run on a computer, a series of 10 video programmes and guided trips to peatlands for children and people with disabilities. PHOTO: METSÄHALLITUS / JOHANNA ROTKO

→ *The oak spider (Aculepeira ceropegia), classified as vulnerable, is primarily found in peatlands in Finland, though elsewhere in Europe it is associated with other open and sunlit habitats.* PHOTO: NICLAS FRITZÉN.

2 Peatland restoration – needs and goals

Kaisu Aapala, Sakari Rehell, Maarit Similä and Tuomas Haapalehto

2.1 Why restore peatlands?

The diversity or Finland's natural peatlands and their flora and fauna has declined due to the actions realised to promote their commercial utilisation, such as the digging of drainage ditches to promote forest growth (Sections 3.4, 4.3 and 5.3), the clearance of farmland, and peat extraction. Even undrained peatlands are widely no longer in their natural state due to actions such as logging, site preparation for forestry purposes, the clearance of streams, the construction of reservoirs, and the extraction of groundwater (Kaakinen et al. 2008, Rassi et al. 2010). Drainage has also had a negative impact on many of the ecosystem services provided by natural peatland ecosystems. Although new ditches are no longer being dug in Finland's peatlands the state of our peatland habitats is still deteriorating due to the impacts of earlier drainage schemes.

The overall goal of peatland restoration is to enable the natural functions and structures of peatland ecosystems to become re-established in areas where they have been affected by human activity. Specific objectives may be achievable within several years (e.g. raising the water table level, Section 3), within several decades (e.g. the reappearance of near natural vegetation communities, Section 5), or perhaps only after centuries (e.g. the structure and dynamics of mature tree communities) (Aapala et al. 2008).

Restoration is not always necessary or recommendable. Restoration work could, for instance, endanger existing cultural or natural features including rare or threatened species that are sensitive to disturbance (Sections 8.1 and 9). Likewise, if valuable old-growth forest features such as abundant and diverse deadwood are present in a drained spruce mire, the benefits and drawbacks of restoration should be very carefully weighed up.

2.2 The ecological objectives of peatland restoration

The need for restoration and the prospects of success should be carefully evaluated for each peatland site before a decision is made to proceed (Section 6). As a basis for all peatland restoration work it is essential to understand both the structure and functioning of peatland ecosystems (Sections 3, 4, 5), and the various impacts of drainage and restoration measures.

The definition of detailed objectives for restoration work i is a vital part of any restoration project (Section 6). These objectives should be used to steer the planning, implementation and impact monitoring phases of the project. Objectives can be defined with help from historical records such as old aerial photographs and maps, as well as data on the present state of comparable natural peatlands as well as the site to be restored.

Hydrology

The structures and species communities of peatland ecosystems are largely determined by their hydrology, so restoration work must strive to re-establish an ecosystem's natural hydrological features as well as possible (Section 3). Each peatland site has its own hydrological characteristics affected by climatic factors as well as the physical and ecological features of its own basin and catchment area.

Goals typically include raising the water table back to near natural levels, and re-establishing natural flows of water through different parts of the mire, resulting in the restoration of naturally varying hydrological features (Sections 3 and 6). In addition to the damming of ditches, the restoration of hydrological features must also involve re-establishing the flows of water that would naturally feed the peatland ecosystem. This is particularly important in minerotrophic peatland sites (Section 3) whose characteristics are largely determined by the quality, quantity and timing of incoming water flows from their catchment areas.

Even poorly maintained ditches typically serve to drain water away so well that ditched peatlands no longer have the kinds of extensive flows of water in porous surface peat layers that characterise natural peatlands. Leaving a drained peatland to "revert by itself" to a natural state may lead to the development of a peatland ecosystem resembling for example a nutrient-poor pine mire, but is unlikely to promote the reappearance of the key features of wet and nutrient-rich peatlands. Active restoration measures are generally needed wherever the goal is to restore natural hydrological processes in a peatland site.

Flora and fauna

The key goals behind peatland restoration are to halt the decline in peatland species (Figure 5) and to trigger a process of ecological succession that will re-establish the near natural functioning of peatland ecosystems. Many potentially restorable drained Finnish peatlands still have sphagnum mosses and other key peat-forming plants that play an essential role in the natural functions of peatlands and in the recovery of other species communities (Sections 4 and 5). But peatland vegetation can only recover effectively if natural or near natural hydrological conditions are restored (Section 3).

Detailed species-specific objectives can be defined for restoration projects: the goal may be to enable typical species to return to a certain part of the peatland, or to manage the habitat of a specific threatened or otherwise significant species (Section 8, Info box 5). Wherever such objectives are specified it is important to consider the respective species' habitat requirements, the location of the site in relation to potential source populations, factors that could limit the species' spread, and factors related to competition between and within species (Mälson & Rydin 2007, Mälson et al. 2008). It is especially important to understand the prospects for species' survival in nutrient-rich peatland habitats, so as to ensure that species still present will continue to survive in spite

Figure 5. *Many peatland butterflies are highly dependent on natural conditions in their habitats, and they quickly vanish from drained peatlands. The frigga fritillary (Clossiana frigga) has generally declined across Finland due to the widespread drainage of peatlands, but just recently the species has begun to reappear in restored peatlands.* PHOTO: JUSSI MURTOSAARI.

of the disturbance caused by restoration work (Sections 8.1 and 11.1).

The changes in species communities induced by drainage are often so drastic that it is impossible to define detailed species-related objectives. Nutrient-rich and wet peatlands particularly change rapidly and greatly after ditches are dug, and few traces of their original natural species communities may be evident (Figure 6). However, peatlands do also evolve naturally over time due to external and internal factors. The goal of restoration should not be to restore the site to its exact condition before drainage, but to strive to trigger a process through which the site will become a peatland ecosystem with near natural functions.

Figure 6. *The species communities of this eutrophic pine fen have changed completely since drainage ditches were dug. The site will be restored by damming ditches and felling and removing the trees that have grown since the ditches were dug. This site lies downstream of natural and previously restored eutrophic pine fen habitat, so it should be possible for some of the original species to return successfully after the site is restored.* PHOTO: SARI KAARTINEN

2.3 Other objectives

It may be possible to restore lost or weakened ecosystem services in restored peatlands, and this goal has recently been raised alongside promoting biodiversity when defining objectives for restoration (Aronson et al. 2006, Society for Ecological Restoration International 2008, Benayas et al. 2009, Kimmel & Mander 2010, Bain et al. 2011, Bullock et al. 2011). The Finnish ecosystem-based approach to peatland restoration also helps to re-establish and reinforce the ecosystem services provided by peatlands.

The most significant of the regulating ecosystem services provided by peatlands in global terms is climate regulation. Mitigating climate change is accordingly one of the goals of peatland restoration (Info box 3). Regulating ecosystem services that are important on a more local scale include water flow and water quality regulation; and peatland restoration also aims to re-establish and enhance these services (Section 3). In the short term nutrients may leach from restored peatlands (Section 6.4, Info box 4), but in the longer term restoration improves the quality of runoff from peatlands.

Drainage also changes the whole landscape. Another goal of restoration is to recreate the natural structural features of the landscape, including areas of open peatland (Figure 7). Landscape restoration goals usually also align with other cultural ecosystem services provided by peatlands, such as recreational amenity value. Hunting is a popular recreational activity in Finland's peatlands, and the restoration of game bird habitats has become an important objective for many restoration projects (Info box 5).

Figure 7. *Restoration work was realised in Haapasuo Bog in Leivonmäki National Park in Central Finland in 2001. The pine trees that had grown on originally open parts of the bog (photo A) were removed before the ditches were blocked. Photo B shows the same part of the bog four years after the trees had been felled and the ditches dammed.* PHOTOS: ANNELI SUIKKI.

The climate impacts of drained and restored peatlands

Eeva-Stiina Tuittila and Jukka Laine

From a climate perspective natural northern peatlands have three important functions: they account for about a third of worldwide soil carbon storage; they fix more carbon dioxide from the atmosphere than they emit; and they account for some 20–30% of annual global methane emissions (Gorham 1991, Turunen et al. 2002, Lafleur et al. 2003, Nilsson et al. 2008). Drainage alters the role played by peatlands in regulating the global climate. A water level drawdown triggers a drying succession in vegetation and microbe communities (Laine et al. 1995b, Jaatinen et al. 2007). When decomposition processes are no longer limited by the lack of oxygen (Fenner & Freeman 2011), soil organic matter (SOM) previously accumulated in anaerobic conditions below the water table starts to decompose more rapidly (Pitkänen et al. 2013), and consequently more carbon dioxide is released into the atmosphere (Martikainen et al. 1995). It is likely that all drained peatlands become net carbon sources for a period of time soon after drainage, before the successional changes in their vegetation start to compensate for the carbon released due to decomposition. These successional changes, which commonly include accelerated tree growth, alter decomposition rates by favouring plant species that produce slowly-decaying litter on the soil surface. Following the drainage succession some peatlands drained for forestry end up functioning as small carbon sinks, while others continue acting as carbon sources (Ojanen et al. 2010, 2012, Lohila et al. 2011). This variation in the carbon sink function is related to nutrient levels and climatic factors: nutrient-rich drained peatlands in Southern Finland are more often carbon sources than nutrient-poor drained peatlands in Northern Finland (Ojanen et al. 2010, 2012). Concurrently with changes in vegetation and carbon dioxide fluxes methane emissions from drained peatlands decline due to a decrease in methane production and increased oxidation. Drained peatlands may even act as small-scale methane sinks (Roulet et al. 1993, Yrjälä et al. 2011).

Raising water table levels as part of peatland restoration slows aerobic decomposition and reduces carbon dioxide emissions, thus stabilising carbon stores and finally turning the peatland back into a net carbon sink (Komulainen et al. 1999, Tuittila et al. 1999, Wilson et al. 2007, Waddington et al. 2010). The restoration succession towards the vegetation and carbon sink functioning typical of pristine peatlands appears to progress faster in nutrient-rich peatland sites than in nutrient-poor sites (Komulainen et al. 1999). However, since nutrient-rich sites are more radically changed by drainage in the initial phase of restoration they are typically further from their natural state than nutrient-poor peatlands, where natural conditions can be re-established more rapidly. Although the restoration succession in vegetation communities promoted by the raising of water table levels (Haapalehto et al. 2010, Laine et al. 2011) is thought to make restored peatlands into relatively small annual carbon sinks similar to natural peatlands, considerable levels of carbon sequestration have been measured in restored former peat extraction sites during the first years after water levels rise (Soini et al. 2010) (Figure 8). While raising the level of the water table reduces carbon dioxide emissions, higher water table levels conversely increase methane emissions (Waddington & Day 2007). Recent research findings indicate that methane emissions from restored peatlands previously drained for forestry remain low more than ten years after restoration. These low emissions have been linked to the low abundance of methane-producing microbes and changes in their microbial community structure (Juottonen et al. 2012). It appears that the natural methane cycle recovers more slowly than the carbon sink function, and that the recovery of the microbial community plays a key role in the re-establishment of the methane cycle.

Figure 8. *Measuring carbon dioxide flows in a restored fen. The amounts of carbon absorbed and released can be measured using closed chambers.* PHOTO: JUKKA LAINE.

The impacts of peatland restoration on water quality

Tapani Sallantaus

Peatland restoration projects aim to re-establish natural processes such as nutrient cycles and the accumulation of nutrients in new peat layers. This in turn is expected to improve the quality of runoff water from restored peatlands, compared to runoff from peatlands with functioning drainage ditches.

Over a short timeframe the raised water tables caused by blocking ditches represent a radical change in conditions for the trees, other vegetation and soil organisms present in drained peatlands. Drainage changes the characteristics of surface peat layers, affecting decomposition, and releasing nutrients for growing vegetation to utilise. Restoration work may initially induce pronounced changes in the quality of runoff.

On the basis of findings from the monitoring of a total of 15 catchment areas and nine separate monitoring sites, a set of reasonably reliable specific load figures can be obtained for restored sites, quantifying the additional leaching of phosphorus, nitrogen and organic carbon into watercourses due to restoration per area of restored peatland. These elements are the leached substances most clearly affected by peatland restoration. Specific loads describing the additional leaching caused by a specific measure, in this case peatland restoration, can only be calculated when all impacts have become evident. In the 15 catchment areas studied, post-restoration monitoring was conducted for an average of 7 years. Prolonging the monitoring period would only have improved the specific load data slightly.

The sites monitored included very different kinds of peatland ecosystem. The peatland sites monitored in five catchment areas in Seitseminen National Park are mainly ombrotrophic or slightly minerotrophic. They were originally sparsely wooded pine mires where ditches had been dug about 30 years previously, with phosphoric fertilisers spread after drainage. Tree cover still remained limited before restoration, with an average of 55 m^3/ha of timber, and the undergrowth still contained many peatland species, including sphagnum mosses (Section 11.7, Koskinen et al. 2011, Sallantaus & Koskinen 2012). Two of the catchment areas included a single lake, with retention times of approximately 0.3 years in each case. The restoration sites at Haapasuo in Leivonmäki National Park (Section 11.5) and parts of the sites at Punassuo are also nutrient-poor pine mires. Restoration has mainly been successful in these nutrient-poor sites (Figure 7, page 10).

More densely wooded nutrient-rich spruce mires were monitored in three catchment areas at Mustakorpi in Nuuksio National Park (Koskinen et al. 2011, Sallantaus & Koskinen 2012) and in the catchment area of Lake Vähä-Ruuhijärvi in Evo. Before restoration these sites had quite dense forest cover, mainly spruce trees, with timber volumes as high as 300 m^3/ha or more in places; and their vegetation communities were mainly similar to those of heathland forests (herb-rich drained peatland forest or *Vaccinium myrtillus* drained peatland forest) (Figure 9). Parts of Mustakorpi had been drained more than 60 years previous to restoration.

Figure 9. *After being drained, this site at Mustakorpi developed into a peatland forest characterised by large spruce trees.* PHOTO: TAPANI SALLANTAUS

Figure 10. *After restoration nutrient-rich peatland vegetation has gained ground in Mustakorpi and many large trees have died.* PHOTO: TAPANI SALLANTAUS

During restoration work trees were not removed, but waterlogging caused deaths of trees and other pronounced changes in vegetation (Figure 10). The retention time of Lake Vähä-Ruuhijärvi is almost a year.

The northernmost monitoring site, at Suuripää, represents rich fens (Räinä 2010). Provisionally usable data on water quality is also available from a rich fen site at Huppionvuori (Section 11.1). The other sites, at Vanneskorpi (Sallantaus et al. 1998, Väänänen et al. 2008, Vikman et al. 2010), Konilammensuo (Silvan et al. 2005), and Hepo-oja (Lehtelä 2005), are fairly nutrient-poor sites where vegetation communities exhibit characteristics intermediate between pine mires and spruce mires.

Table 1 shows the findings from the best documented sites. Phosphorus loads were high for the nutrient-poor pine mires in Seitseminen and for nutrient-rich spruce mire sites. Haapasuo had the lowest specific loads, though the quantities leached at Suuripää were also low.

Specific loads at nutrient-poor Punassuo are similar to those observed in Seitseminen. Vanneskorpi had high figures for leaching and the highest specific loads among all the data (Sallantaus et al. 1998), while specific loads were lowest at Konilammensuo and Hepo-oja (not shown in the table).

The loads of the three water quality factors are interrelated, but specific loads of nitrogen and organic carbon are proportionally larger in relation to phosphorus loads in more nutrient-rich peatland sites. It is particularly significant that a considerable part of the nitrogen mobilised in nutrient-rich mires is inorganic, e.g. about a quarter at Mustakorpi, but just a few per cent in nutrient-poor sites such as Seitseminen.

In five separate areas out of nine specific loads were significant and of the same scale as those caused by first-time drainage or forest regeneration (Section 3.4), or sometimes even higher for phosphorus. The sites with high loads are both nutrient-rich and nutrient-poor. The high specific loads at Vanneskorpi can be explained by the peatland site's very extensive catchment area, which results in large flows of water that have effectively leached available nutrients out of the peatland site.

Table 1. *Specific loads of nutrients additionally leached due to peatland restoration at the best documented sites. n = number of catchments. Imprecise values are italicised.*

	Total P kg/ha	Total N kg/ha	Organic C kg/ha	n	ref
Seitseminen	2.6	14	700	3	Koskinen et al. 2011
Seitseminen lakes	3.6	14	560	2	
Mustakorpi	1.7	22	900	1	Koskinen et al. 2011
Vähä Ruuhijärvi	3.5	9	340	1	
Haapasuo	*0.1*	*0.6*	*30*	1	Section 11.5
Suuripää	*0.7*	*4*	*100*	1	Räinä 2010

Of the sites with low load figures, the peatlands at Konilammensuo, at Hepo-oja, and in parts of Haapasuo are all rich in iron. The abundance of iron is known to be a highly significant factor regulating the leaching of phosphorus (Zak et al. 2010) and organic carbon (Knorr 2013). At Konilammensuo logging residues were carefully removed, but this was also generally done at the sites in Seitseminen. The forest fertilisation realised after the sites in Seitseminen were originally drained may account for the high figures for phosphorus leaching. At the three northernmost sites the figures for leaching were low, reflecting both the cooler climate, and the fact that conditions in the peatlands had not changed as radically since drainage as in more southerly sites.

The impacts of any lakes in the catchment area on specific loads seem to be limited, though loads of nitrogen and organic carbon seem to be lower in relation to phosphorus loads as a consequence of lacustrine processes including decomposition and sedimentation.

By the end of the monitoring period at many sites loads had returned to almost their pre-restoration levels. The longest monitoring period continued until ten years after restoration. In Seitseminen phosphorus leaching peaked at high levels 1–2 years after restoration, but then decreased rapidly. In the spruce mire sites at Mustakorpi and Vähä Ruuhijärvi evapotranspiration from trees kept the peatland sites dry even though ditches had been blocked, so the period of increased leaching was prolonged.

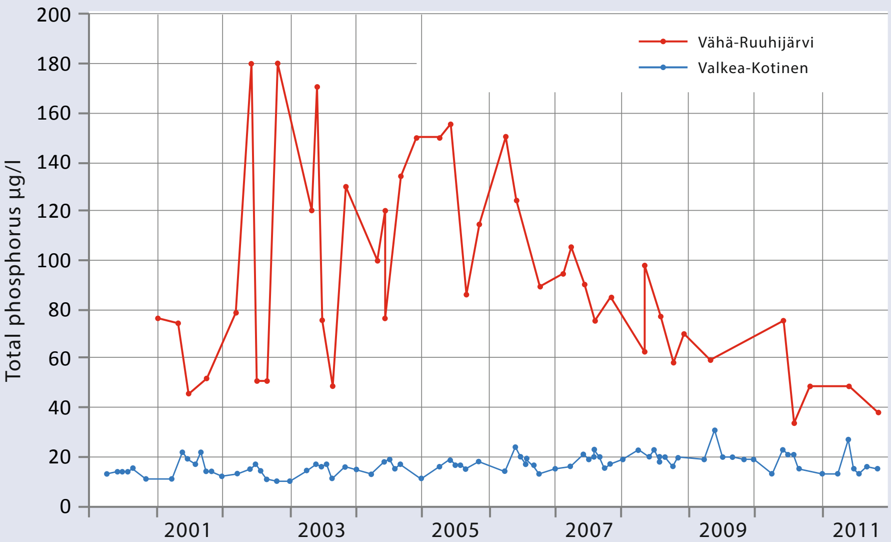


Figure 11. *Total phosphorus concentrations in the surface waters of Vähä-Ruuhijärvi and Valkea-Kotinen, 2000–2011. Peatland restoration work was realised in about a fifth of the catchment area of Lake Vähä-Ruuhijärvi in 2001. Valkea-Kotinen is a nearby lake whose catchment area is completely in its natural state. Initial concentrations in Lake Vähä-Ruuhijärvi were already higher than normal since a beaver dam had earlier raised its water levels. Valkea-Kotinen: concentrations at a depth of 1 metre. Vähä-Ruuhijärvi: concentrations either at a depth of 1 metre or in the stream channel that drains the lake (average figures when concentrations were measured in both locations).*

Pronounced load peaks occurred after wet years until several years after restoration. Increases in post-restoration leaching levels were clearly more prolonged for organic substances and nitrogen than for phosphorus (Koskinen et al. 2011).

The impacts observed in lakes downstream were completely different in the nutrient-poor sites in Seitseminen when compared to impacts affecting the nutrient-rich spruce mire sites at Vähä-Ruuhijärvi. In both cases phosphorus concentrations rose after a brief time-lag to more than 100 µg/l, but under the acidic conditions prevalent in Seitseminen the lack of nitrogen prevented eutrophication, and A-chlorophyll concentrations were never higher than 14 µg/l. In the catchment area of Lake Vähä-Ruuhijärvi, which is characterised by spruce mires, restoration also mobilised nitrogen, and phosphorus concentrations of more than 70 µg/l were still observed annually in the lake seven years after restoration. Phosphorus concentrations returned to pre-restoration levels in just under 10 years (Figure 11).

Conclusions

The most serious water quality problem triggered by peatland restoration concerns the risk of a steep increase in phosphorus leaching. This phenomenon occurred in more than half of the sites monitored. It is not easy to predict where worryingly high downstream loads will occur. Enhancing predictability in order to prevent negative impacts would be an important area for future studies. This is an issue that does not only affect peatlands in protected areas, since commercial forestry is likely to be abandoned in many areas of unproductive drained peatlands around Finland, and the active restoration of their peatland ecosystems is one alternative for their future management.

Restoring the habitats of willow grouse and other game birds

Ahti Putaala

Populations of willow grouse (*Lagopus lagopus*) in the boreal zone of Finland have been declining over the last 30 years. In the south willow grouse have vanished from many areas, and their remaining populations are isolated. This trend is thought to be due primarily to the decline and degradation of their natural habitat caused by the drainage of peatlands. As the climate becomes milder the shorter snowy season and consequent increased predation could also be speeding their decline.

The conservation and recovery of willow grouse populations can be promoted by restoring the peatland habitats where they mate and breed. In commercially managed forests owned by the Finnish State selected areas where willow grouse and wild geese breed are routinely restored as part of normal forestry operations. Measures are also taken to restore small, drained wetland hollows and spruce mires surrounded by heathland forests, so as to provide suitable habitat where game birds can raise their young. These measures have been financed using income from the sale of hunting permits for State lands.

By the end of 2012 a total area of about 2,400 hectares of willow grouse peatland habitat had been restored, mainly consisting of nutrient-poor pine bogs. The restoration methods used are the same as for peatlands in protected areas. Relatively minor additional resources are required for planning and implementing such work, since measures can be realised together with other more routine forestry operations. Ditches in areas to be restored can for instance be blocked at the same time as ditches are cleared and maintained in nearby areas not designated for restoration.

The suitability of restored peatland sites for willow grouse has been studied by tracking and mapping the spring territories of radio-tagged birds. New spring territories have been occupied in restored sites, and other restored peatland sites have also been used for nesting and raising young fledglings (Figure 12).

Figure 12. *This male willow grouse has established his spring courtship territory in a restored peatland site.* PHOTO: TIMO ESKOLA.

3 The hydrology of peatlands

Sakari Rehell, Tapani Sallantaus, Teemu Tahvanainen, Tuomas Haapalehto and Samuli Joensuu

3.1 Water table levels and the origins of peatland water

The water present in peatlands consists of water that has fallen onto them as precipitation and water that has flown into them from surrounding areas as runoff (Figure 13). The characteristics and functioning of minerotrophic peatlands are always connected to conditions in their catchment areas, i.e. the surrounding areas from where runoff flows towards the peatland. It is essential to examine the hydrology of the whole catchment area when planning peatland restoration projects (Section 6.1).

Naturally flowing waters can be divided into surface water, soil water and groundwater. Surface water may form temporary or permanent ponds, flarks, pools and rivulets. Groundwater fills pores in the ground and bedrock. Soil water consists of water kept in the soil by capillary action as well as water percolating downwards due to gravity. Peatlands particularly contain a lot of capillary water, especially in decomposed peat. Capillary water commonly rises in peat by at least a metre (Päivänen 1973). In well-decomposed peat water only moves very slowly, whether by capillary action or due to gravity. This slow movement of water can affect the availability of water to plants.

In natural peatlands the water table lies near the surface of the peat, and the seasonal variations in the water table and total water reserves are usually relatively small. If the soil below a peatland is highly permeable to water then the water table may fluctuate more.

3.2 Water flows in peatlands

Water flows through peatlands as surface runoff, in pores in the peat, and in the ground beneath the peat.

Surface runoff mainly occurs during flood peaks, in Finland most notably during the spring thaw. During the growing season water flows in peatlands mainly occur in the pores within the peat. These flows determine the conditions for peatland vegetation.

In the ground beneath the peat water flows according to the gradient of the water table, and flows are stronger where the ground is more permeable. Groundwater flows are limited in the poorly permeable moraine soils predominant in Finland. This means that water flowing in from the peatland's catchment area largely flows through the peat. Where runoff water from the catchment area flows through fairly permeable soils or underground streams beneath the peat then it does not significantly affect the peatland vegetation.

3.3 Water quality in peatlands

The precipitation that falls onto peatlands and the runoff that flows into them from surrounding areas have quite different chemical properties. Rainwater and snow contain very low concentrations of dissolved substances, and natural precipitation is slightly acidic. Runoff flowing through soil gradually dissolves carbon dioxide, mineral-ions and acidic organic substances.

The characteristics of the soil affect the concentrations of dissolved minerals. In areas with moraine soils most of the runoff entering peatlands arrives during the spring thaw or periods of heavy rain, when a lot of water moves through the topsoil. During such wet spells the concentrations of alkali cations are lowest, but organic substances, iron and aluminium are all leached from the topsoil. In areas with permeable soil no runoff flows through the topsoil, and the organic substances leached from the topsoil into the recharging water are retained in the illuviated soil horizon together with iron and aluminium.

Similarly in areas with moraine soils some precipitation percolates down into the groundwater. Groundwater may discharge into peatlands in places, reflected in the presence of demanding plant species. If easily soluble calcium-rich minerals are present, calcium concentrations in groundwater may rise steeply, reflected in the occurrence of plant species that thrive in (or can tolerate) high levels of calcium. Similarly groundwater may in some areas contain high concentrations of magnesium or sodium, which affect the peatland vegetation in the same way as calcium (Tahvanainen 2004).

In anoxic soil layers iron is dissolved in soil water. It then precipitates in springs or flarks where groundwater is discharged into peatlands. Concentrations of the key nutrients nitrogen and phosphorus are

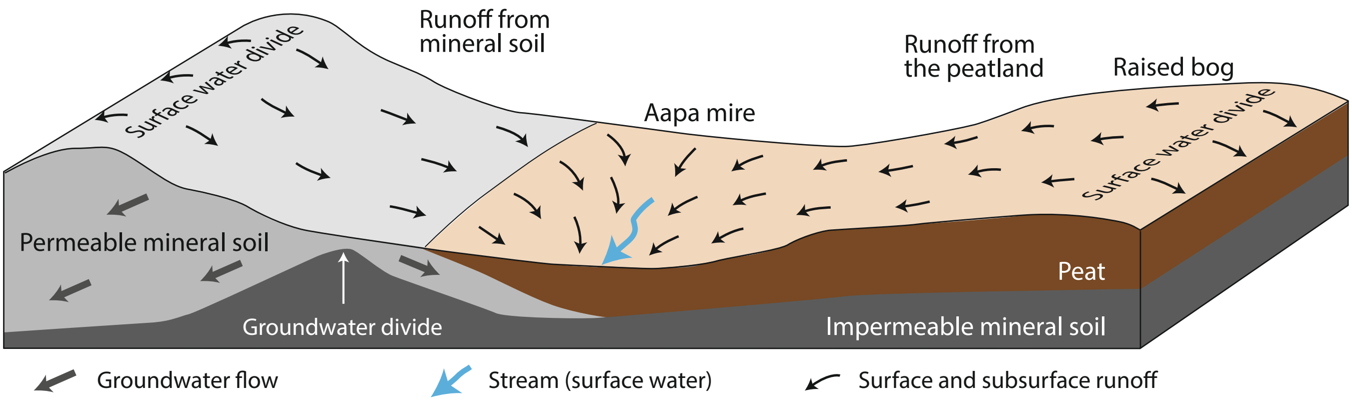
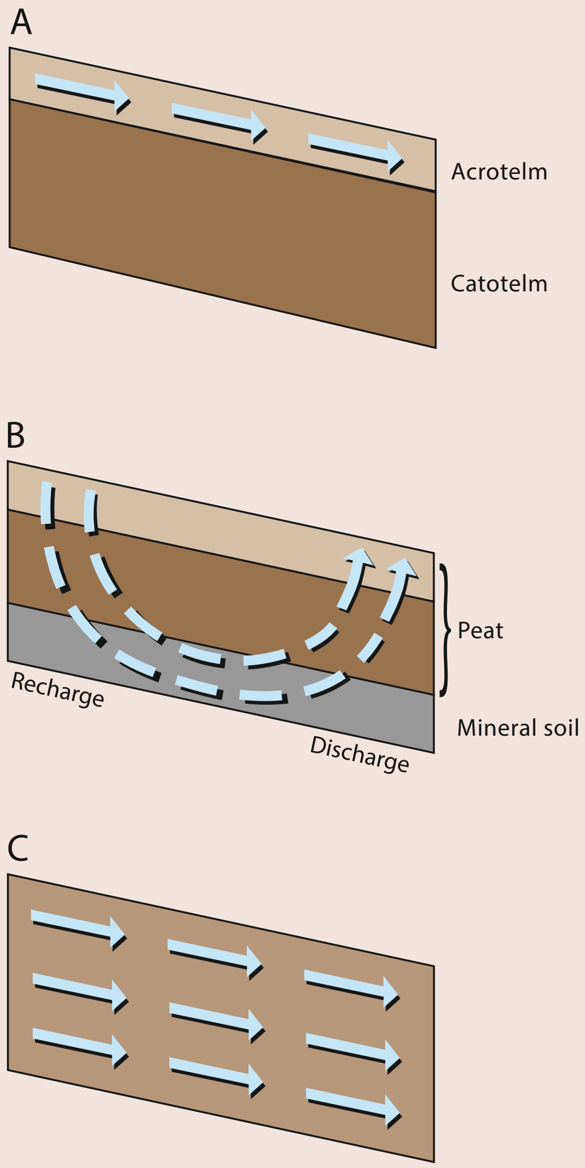


Figure 13. *Flows of surface runoff and groundwater, and the locations of surface water and groundwater divides.*



FLOW MODELS FOR PEATLAND WATER

The permeability of peat layers determines where water flows are concentrated. Three simplified models are used to help describe complex flow systems: A) diplotelmic model; B) peatland integrated into groundwater flows; C) percolation model.

A) Most peatlands in the boreal zone can be well described using the diplotelmic model (Ivanov 1981, Ingram 1983, Laitinen et al. 2007), which has two clearly distinct layers of peat. The surface peat layer (acrotelm) is porous and highly permeable to water. The sub-surface peat layer (catotelm) is denser and only slightly permeable to water. This model assumes that no water flows through the catotelm, meaning that all the water flows through the acrotelm according to the gradient of the water table in the peatland. The acrotelm has a self-regulating mechanism. When water is abundant, the water table rises and outflows intensify. When there is less water, the water table drops to the lower boundary of the acrotelm, and outflows decline, eventually to zero.

The diplotelmic model has particularly been devised to describe the hydrology of raised bogs, but its basic assumptions can be considered as applying to most of Finland's peatlands. Although in aapa mires and raised bogs with many flarks the surface may largely consist of exposed peat, with no diplotelmic structure, variations in the water levels in the areas of exposed peat are largely regulated by elongated hummocks whose structure is diplotelmic.

B) Peatlands integrated into groundwater flows. Water flows through such peatlands as part of the wider recharging and discharging of groundwater, with flows also occurring vertically between peat layers and the ground beneath (Laitinen et al. 2008). In areas where the groundwater is recharged water flows downwards through the peat, while in areas where groundwater is discharged it rises up towards the surface.

C) In percolation mires water flows through thick layers of porous peat. True percolation mires (Joosten & Clarke 2002) are rare in Finland. But spring-fed or swamp fens with evidently thick layers of permeable surface peat and a permeable sub-surface layer of sedge peat typically exhibit water flows that resemble those in percolation mires.

usually low in natural groundwater, where nitrogen levels are often lower than in rainwater.

The movements of water and water quality are closely interlinked. Peatlands capture and store chemical elements from the water that flows through them by means of biological and chemical processes. These substances accumulate in peat, but at the same time substances including organic acids formed during the partial decomposition of plant matter are dissolved into the water from the peat, significantly affecting water acidity (Hemond 1980, Tahvanainen et al. 2002). The stronger the flow of water through a peatland, the faster organic acids will be leached out of the peat. The pH of the water is the result of the balance between organic acid concentrations, mineral alkalinity and carbon dioxide. The pH of the water is the chemical characteristic most closely linked to the development of vegetation communities (Tahvanainen 2004). High mineral concentrations in groundwater, for instance in calcareous fens, increase the alkalinity of the water and effectively neutralise the effects of organic acids even when water inflows are more limited.

Mosses are the best indicators of water quality among peatland plants. Moss species assemblages are indicative of trophic levels, which particularly reflect the pH of the water. At the ombrotrophic end of the scale, where nutrient levels are lowest, are raised bogs, which only receive water from precipitation. The pH level of the water in raised bogs is usually less than 4.2, and calcium concentrations are lower than 0.5 mg/l. Moss communities include species tolerant of acidic conditions, such as sphagnum moss species associated with nutrient-poor peatlands. It is noteworthy, however, that no sphagnum moss species is limited exclusively to ombrotrophic peatlands.

In minerotrophic peatlands the water contains varying quantities of dissolved minerals originating from areas with mineral soils. At the nutrient-poor end of the minerotrophic range, in oligotrophic peatlands, vegetation communities and water chemistry do not differ much from those in ombrotrophic peatlands (Tahvanainen et al. 2002). It should be noted that sedges indicative of minerotrophic conditions may also occur in peatlands that are ombrotrophic in terms of the chemistry of their surface water, if the sedge roots are able to reach deeper, more minerotrophic peat layers (Tahvanainen 2011).

In mesotrophic peatlands and in rich fens, plants requiring high pH levels thrive, while species more associated with nutrient-poor conditions are absent or only occur in hummocks or other locations away from inflowing water. Concentrations of dissolved minerals and pH levels are both higher than in peatlands with lower trophic levels. In oligotrophic conditions pH values are typically under 5, while in mesotrophic conditions they are 4.5–6. The water in rich fens is often almost neutral, though pH values may vary between 5.5 and 8.5. The pH values observable under differing trophic conditions thus overlap considerably. One reason for this is fluctuations in carbon dioxide concentrations, which lead to variation in pH values even at different times of day (Tahvanainen & Tuomaala 2003). There is also considerable overlap for other chemical indicators of trophic levels, such as calcium concentrations, as well as sizeable variations between different nutrient levels. Rich fen vegetation sometimes indicates calcium-rich conditions even at calcium concentrations as low as approx. 2 mg/l (Tahvanainen et al. 2002), though in rich fens in areas with truly calcium-rich conditions concentrations of more than 20 mg/l are common.

3.4 Impacts of drainage on peatland hydrology and loads in river basins

Drainage lowers the water table in the peat in order to promote tree growth by deepening the oxic soil horizon. The goal is typically to create a layer of aerated soil at least 40 cm deep (effective ditch depth) on the surface of the peatland (Päivänen & Hånell 2012).

Drainage schemes account for the natural flow directions of the water in the peatland. The main drainage ditch is often located in the lowest part of the peatland with the other feeder ditches entering it aligned diagonally with respect to the gradient of the

GROUNDWATER-FED PEATLANDS

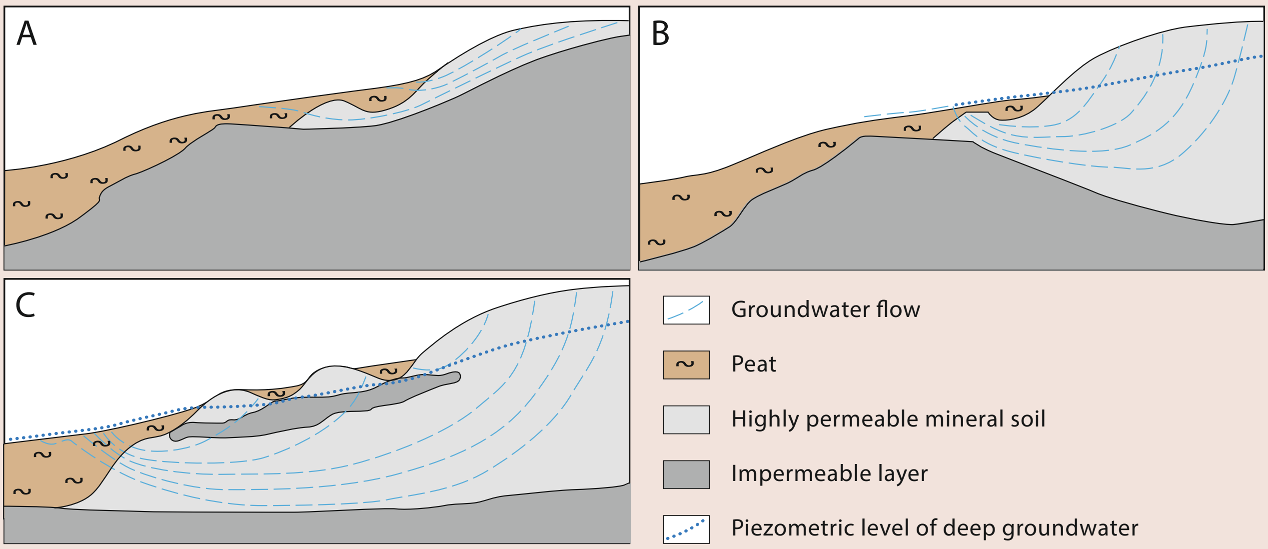
Where groundwater is formed in the peatland itself or is discharged to the peatland through the peat layer a three-dimensional approach needs to be applied when examining their hydrology (Heikkilä et al. 2001, Laitinen et al. 2007).

A) In Finland the terrain typically consists of a fairly thin layer of moraine deposits overlying gently undulating impermeable bedrock. Runoff from mineral soils flows on or near the surface. This water discharges into peatlands at the edge of the mineral soil, and only has a minor groundwater effect, typically limited to small seepage areas on the margins of mires. Defining the catchment area of this kind of peatland is a straightforward process, and such peatlands can be assumed to resemble the diplotelmic model.

B) One common feature in Finland is the immediate juxtaposition of a permeable esker formation bordering on a peatland with an impermeable base. Plenty of groundwater typically accumulates in eskers, since almost all precipitation rapidly percolates through their sandy soil into the groundwater. In elongated eskers groundwater may also flow long distances from where it is first accumulated. Groundwater is discharged from larger esker formations quite evenly all year round. Where it is discharged into a peatland it typically wells up in large open springs on the margin of the peatland and the mineral soil of the esker. This spring-water may flow onward as a stream, in which case the discharged groundwater may not be dispersed through the peatland at all.

Where peatlands are fed by groundwater from esker formations their hydrology differs greatly from conditions in areas with more typical moraine soils. They receive water throughout the growing season, so the peatland itself may also discharge plenty of water even during drier seasons.

C) In areas with deep soils exhibiting pronounced layering, such as ice marginal formations, groundwater may flow quite different distances in different soil layers (Heikkilä et al. 2001). Peatland ecosystems linked to such formations may be highly diverse. In some places water may well up to the surface, while elsewhere it may seep back down into the groundwater and flow for up to several kilometres through permeable ground layers. Many different types of peatland habitat may occur, ranging from spring fens and seasonal wetlands to rich birch fens. In such areas the impacts of different actions, including both drainage and restoration, may cover extensive areas and be hard to predict.



peatland to optimise drainage. Intercepting ditches are dug along the boundary between the peatland and the surrounding areas with mineral soils to intercept any surface runoff that would otherwise enter the peatland.

Drainage increases runoff rates. Larger quantities of water are discharged from the peatland, reflected in the drying out of the peat and the sinking of the surface. The total change in the quantity of water stored in the mire is most typically of the order of 300 – 400 mm, corresponding to a year or more of runoff. Increased runoff also reduces evaporation from drier peatlands. In drained, wet and sparsely wooded peatlands evaporation may initially decline by as much as hundreds of millimetres a year, and the increase in runoff compared to the situation before drainage may be prolonged for up to 20 years (Seuna 1981). Runoff particularly increases during periods of low runoff such as summer and midwinter.

The peat eventually becomes gradually denser and its diplotelmic structure disappears. As the permeability of the denser peat declines, variations in the water table become more pronounced (Päivänen 1973) and minimum runoff levels gradually decrease. Total runoff is primarily reduced by the increased evapotranspiration from trees.

Findings on the impacts of drainage on maximum runoff levels during monitoring periods are somewhat contradictory, but in general maximum runoff levels have been observed as increasing (Seuna 1981, 1982, 1988, Verry 1988, Sirin et al. 1991, Johansson & Seuna 1994, Holden et al. 2004). Although the impacts of tree cover in terms of evapotranspiration are significant, since for instance the evapotranspiration from 100 m^3 of growing timber in one hectare reduces water levels during the summer by an average of 20 cm (Lukin 1988, Vasander & Lindholm 1989), the risk of increased summer flooding can be considered as a permanent consequence of peatland drainage (Seuna 1981, Ahti 1987).

Drainage also significantly affects water quality. The impacts of drainage are intensified in minerotrophic peatlands that have developed due to inflows of water from their catchment area, where ditches intercept inflows from the catchment area. This water no longer recharges the peatland, inhibiting the ability of the peatland to filter various substances from the incoming water. Substances previously accumulated naturally by the peatland also begin to be leached away.

Specific loads in terms of increased leaching of newly drained peatland over a ten-year period have been measured at 1.6 kg/ha for phosphorus and 21 kg/ha for nitrogen (Ahtiainen & Huttunen 1999, Kenttämies 2006). The impacts of drainage do not end within ten years, however, since drainage results in permanent hydrochemical changes in processes in the catchment area. In older drained peatland areas monitoring has indicated that leaching of phosphorus and nitrogen increase respectively by factors of 3 and about 1.5 compared to natural catchment areas (Joensuu 2002, Kortelainen et al. 2006).

Nutrient leaching in drained peatlands is also increased by the clearing of older ditches, supplementary ditching, the felling of trees, and fertilisation. The specific loads of phosphorus and nitrogen caused by ditch clearances are lower than those induced when ditches are first dug (Joensuu 2002, Finér et al. 2010, Åström et al. 2001b, 2005). Specific loads induced during forest regeneration have been measured for phosphorus at 0.64 kg/ha and for nitrogen at 25.9 kg/ha (Finér et al. 2010).

Peatland drainage also affects the leaching of dissolved organic carbon (DOC) in many ways. Increased runoff promotes the leaching of DOC, but at the same time the reduced runoff through the surface peat layers reduces it (Sallantaus 1988). After drainage water flows occur deeper in the ground, which particularly in shallow peatlands may be reflected in lower DOC concentrations in runoff quite soon after first-time drainage or the re-clearing of drainage ditches (Hynninen & Sepponen 1983, Lundin 1988, Joensuu 2002, Åström et al. 2001a, 2005). Drainage nevertheless increases DOC concentrations in the surface layers of the peat, since organic material is no longer diluted or leached away by runoff from the catchment area (Sallantaus 1995). The long-term monitoring of river basins has not yet resulted in clear findings on the impacts of peatland drainage on downstream humus concentrations (Metsä- ja turvetalouden vesiensuojelutoimikunta 1988, Räike et al. 2012).

First-time drainage generally has a neutralising impact on the acidity of runoff (Heikurainen et al. 1978, Ramberg 1981, Hynninen & Sepponen 1983, Sallantaus 1983, Lundin 1987, 1988, Berry & Jeglum 1991, Manninen 1998, Ahtiainen & Huttunen 1999, Prévost et al. 1999). The re-clearing of drainage ditches has a similar impact (Joensuu 2002). In certain conditions, however, drainage may increase the acidity of runoff, at least occasionally, e.g. in sulphur-rich peatlands in areas with acid sulphate soils (Saarinen et al. 2013). If the peat layer throughout the area impacted by drainage is ombrotrophic, drainage does not increase pH values in runoff (Sallantaus 1983, 1992).

Drainage evidently acidifies the surface layer of peatlands (Lukkala 1929, Vahtera 1955). The most important process behind this acidification is an increase in concentrations of soluble humic material in the peatland groundwater. Humic substances leach variable cations from the peat into the peatland water and runoff, leading to a reduction in reserves of alkali cations in the peatland (Laiho & al. 1999, Haapalehto et al. 2014). The uptake of nutrients by growing trees also reduces nutrient levels in the peat.

Loads of suspended solids increase greatly where ditches are dug (Metsä- ja turvetalouden vesiensuojelutoimikunta 1988, Holden et al. 2004 & refs.). The consequent impacts have been more serious in smaller water bodies (Vuori et al. 1998). Current guidelines emphasise the need for measures to reduce the leaching of suspended solids, e.g. with the help of sedimentation ponds, overland flow areas, and buffer zones left alongside streams.

3.5 Impacts of restoration on peatland hydrology and loads in river basins

Peatland restoration usually raises the water table very rapidly (Tahvanainen 2006, Aapala & Tukia 2008, Autio 2008, Laine et al. 2011). During early peatland restoration work the most typical problem was that water flows continued to concentrate on the lines of the blocked ditches leaving the rest of the peatland too dry. In some cases measures were under-scaled, for instance where ditches were blocked only with individual dams and no peat embankments were constructed (e.g. Section 11.5). Restoration methods have been subsequently improved over more than 20 years, but restoring natural hydrological conditions to peatlands still cannot be considered as a straightforward process where success can be assured.

Excessive waterlogging is seldom problematic in restored peatlands. Such problems may however arise in spruce mires and spring-fed areas, or where water is fed into peatlands in point locations or from wider areas than would be natural.

The chances of success in restoration projects are better where conditions have not changed so much since the peatland was drained. In drained nutrient-poor peatlands still covered by continuous sphagnum moss growth, for instance, the structure of the acrotelm layer regulating hydrological conditions will probably revert to near natural conditions relatively rapidly. The presence of well-defined elongated hummocky strings also improves the prospects for success, since such features reinforce the effects of dams, and raised water levels will often be sufficient to restore natural functions in areas that originally had exposed peat or limited sphagnum moss growth. Conversely it is more difficult to restore natural hydrological conditions in peatlands that have changed greatly since they were drained, and therefore lost their original peatland vegetation and the natural structural features of surface peat layers. Such peatlands were often naturally nutrient-rich, sloping sites with abundant through-flows of water.

The redevelopment of peatlands' natural hydrology and vegetation are closely interconnected: hydrological conditions will only be effectively restored where the main features of the vegetation are re-established, and vice versa. Infilled ditches typically remain wet with little vegetation cover after restoration work. Particularly where water flows continue to follow the lines of ditches moisture conditions may vary greatly, and the accumulation of surface peat may be much slower on infilled ditches compared to the areas between ditches, meaning that the old ditch channels will continue to be lower-lying. Especially in nutrient-rich peatlands with pronounced flows of water, the channels of former drainage ditches may remain permanently evident after restoration if too few peat embankments have been constructed or they do not function well.

One of the goals of restoration is to re-establish the natural hydrological functioning of the entire peatland complex. Though completely natural hydrological conditions may not be restorable in all parts of a peatland, even deficiently restored parts may play an important role in terms of efforts to re-establish the hydrology of the whole complex. Even the poorly restored margins of aapa mires, for instance, may be crucial if they can channel water through to parts of the undrained peatland that had dried out. Such measures can thus halt the deterioration of peatland ecosystems even far away from the restored area. Impacts may be particularly extensive where water tables are raised in peatlands overlying highly permeable sand or gravel.

Little data is available on the impacts of restoration on runoff and its variability. In principle these impacts should be the opposite of the impacts of drainage. After restoration a peatland becomes waterlogged: the water table rises, dry peat becomes wet, and the surface rises as the peat swells. The effective ditch depth is relatively small, and the increase in the water reserves in the peatland caused by restoration generally only reduces runoff compared to pre-drainage levels during the year restoration is realised. The longer-term impacts of restoration on runoff depend significantly on trends in evaporation. In sparsely wooded peatlands evapotranspiration from trees is limited, and evaporation from the newly waterlogged ground and proliferating vegetation will most likely increase, reducing runoff. Where tree cover is denser, the way tree stands are managed or otherwise develop after restoration can have a crucial impact on changes in total runoff. Reducing tree cover also reduces evaporation, but increasing the areas of wet surfaces has the opposite effect.

Many studies have shown that peatland drainage can also increase maximum runoff levels (Ahti 1987, Seuna 1981, Holden et al. 2004), so these levels are likely to decline after restoration.

When ditches are blocked water levels rise and vegetation dies. Runoff from the catchment areas of minerotrophic peatlands spreads through them, leaching the peat. These trends may all have harmful impacts on water quality in aquatic ecosystems downstream (Info box 4). The most serious water protection problem relates to the increased leaching of phosphorus. This has been observed in many monitored restoration sites.

Any harmful downstream impacts will most seriously endanger small water bodies. Water bodies downstream of restored sites may also be negatively affected by the impacts of forestry work. The specific loads caused by forestry measures are typically about as large as or even larger than those induced during restoration work (Finér et al. 2010, Kenttämies 2006, Section 3.4 and Info box 4).

It is very difficult to completely avoid such negative impacts, since the substances involved are dissolved in water. Carrying out work over a longer period at different times is one possible solution.

Some restoration sites do not generate any significant loads, however, and restoration may improve the state of downstream water courses immediately after measures are realised. Restoring the drained margins of aapa mires, for instance is likely to improve the quality of downstream water bodies, while also evening out flood peaks, since water from the catchment area will be redirected along its natural routes into the undrained central parts of the mire, instead of by-passing the mire in drainage ditches.

In the longer term restoration can be expected to affect the quality of runoff positively. There is evidence of this from various studies, including one in the British Isles, where peatland restoration was found to have improved water quality and boosted biodiversity in streams and rivers downstream (Ramchunder et al. 2012).

4 Surface peat and peat formation

Teemu Tahvanainen and Tuomas Haapalehto

4.1 Peat formation in natural peatlands

Peat forms when dead parts of plants remain partly decomposed in water-saturated anoxic conditions. Peat accumulates wherever the dead plant matter decomposes more slowly than new plant matter grows. In sphagnum bogs, for instance, sphagnum moss often grows at a rate of several centimetres a year. The rate of peat accumulation is on average much less than this, however, since lower peat layers decompose and become more densely packed. The average rate of peat accumulation in peatlands in Finland has been estimated at 0.3 mm a year, and the highest rates of long-term accumulation are around 3 mm a year (Mäkilä 2006). Although peat only accumulates slowly, it plays a highly significant role in the global carbon cycle. About 90% of its total weight consists of water, but carbon accounts for about 50% of its dry weight. It has been estimated that the peat in all the peatlands of the Northern Hemisphere contains some 547 petagrammes of carbon (Yu 2011; Pg = 1015 g), amounting to about 40% of all the carbon stored in soils around the world, and corresponding to about 70% of the carbon dioxide in the atmosphere. According to more cautious estimates, boreal peatlands contain 275–455 Pg of carbon (Turunen et al. 2002).

Sphagnum mosses annually produce on average 150–320 grammes (dry weight) of biomass per square metre, corresponding to 75–160 grammes of carbon (Lindholm & Vasander 1990). Peatlands dominated by sedges usually have higher productivity, though it can generally be stated that peatlands are not particularly productive environments, and peat formation is not a direct consequence of biomass production. The rate of peat accumulation is instead crucially dependent on the rate of biomass decomposition. The factors that limit decomposition play an extremely important role in peat formation. Most of the organic matter in a peatland decomposes in the oxic surface layer of peat, known as the acrotelm (see page 17: flow models, the acrotelm and the catotelm). Decomposition progresses particularly rapidly in the lower part of the acrotelm, near the water table. In the peat layers below the acrotelm, known as the catotelm, decomposition is considerably slower. The key stage of peat formation can be considered as the phase when the partly decomposed organic matter becomes part of the catotelm.

Natural peatlands in Finland typically accumulate about 10–30 grammes of carbon per square metre per year. In raised bogs the long-term carbon accumulation rate averages 21 g/m^2/year, while in minerotrophic peatlands the average rate is 17 g/m^2 (Turunen et al. 2002). The annual accumulation rates are larger when shorter time periods are considered. This is because peat decomposition continues at a very slow rate also in the catotelm in older peat deposits. Shorter-term accumulation rates are useful for instance when comparing the changes recently induced by drainage and restoration.

In sphagnum bogs new layers of sphagnum peat form on top of older layers. Peat formed from sedges contrastingly consists largely of the remains of the roots of sedges. Since these roots extend deep into the peat, sedge peat does not exhibit such clear chronological layering as sphagnum peat. But it is still possible in principle to define an acrotelm in the surface layer of sedge peat where various processes occur before the peat becomes part of the deeper catotelm and enters longer term “storage”. Peatland drainage and restoration both affect the regulation of water levels most clearly in the surface peat layers, thus shifting the boundary between the acrotelm and the catotelm. In deeper peat layers the impacts of drainage and restoration are much less evident.

4.2 The dynamics of peat decomposition

The decomposition of plant matter is affected by the characteristics of the plant matter itself and by the conditions for decomposition. Peatlands are unique environments where the formation of peat is favoured by conditions that slow the decomposition of plant matter. The most important of these conditions is a shortage of oxygen due to wetness. Decomposition rapidly consumes oxygen in the water that fills the pores in peat layers, and since water only flows through peat slowly, oxygen cannot effectively reach the catotelmic peat layers beneath the water table from more aerated surface peat layers. Anoxic conditions are widespread in peatlands in water-saturated pores even above the water table. On the other hand, vascular plant roots extending deep into the peat can transport oxygen and break the boundary between the peat layers formed by the water table, where oxygen is available. The volume and speed of water through-flow also affect the availability of oxygen.

In addition to anoxicity, decomposition is often limited by acidity, by shortages of nitrogen and other nutrients and minerals, and by the comparatively low temperatures typical in lower peat layers. Moreover, sphagnum mosses in particular have biochemical properties that also evidently slow decomposition. In deep raised bogs many factors combine to slow decomposition: all nutrients are in short supply, pH levels are low, the insulating surface layer of peat keeps temperatures low in deeper layers, there are few plants with deep roots that could transport oxygen, and a large part of the plant biomass consists of poorly decomposing sphagnum mosses. In aapa mires peat usually decomposes faster than in raised bogs, and peat layers are shallower, because nutrients are more available, pH levels are higher, greater through-flows of water and the abundance of sedge roots both increase the availability of oxygen for decomposers, and the plant biomass itself is more easily decomposed.

Plant matter is decomposed through a series of biochemical reactions catalysed by many different enzymes. In peatlands anoxicity and acidity both reduce the activity of the phenol oxidase enzymes that catalyse the oxygenation of phenol (aromatic) organic compounds (Freeman et al. 2004). This increases phenol concentrations in organic substances, since the oxygenation of phenolic compounds is inhibited. High phenol concentrations in turn slow or prevent the action of other enzymes in the decomposition chain. Low pH levels are also known to limit phenol oxidase (Tahvanainen & Haraguchi 2012), and in nutrient-poor peatlands shortages of nitrogen also reduce the activity of phenol oxidase (Bragazza et al. 2006). Contrastingly, high concentrations of iron, for instance may promote the oxygenation of phenol even where oxygen is in short supply (van Bogedom et al. 2005).

Rates of decomposition and thus peat formation can be affected by many different factors where conditions change due to drainage or restoration.

4.3 The impacts of drainage on peat formation

Intensive peatland drainage effectively stops peat accumulation. Though litter still forms on drained peatlands as vegetation dies, it no longer ends up in a water-saturated catotelm, which can be considered as a precondition for peat formation. The surface peat layer above the catotelm in drained mires consists of fresh litter together with old peat formed before drainage. The thickening of the oxic surface peat layer of the acrotelm promotes decomposition. Additionally, the surface peat layers tend to sink greatly due to the loss of the water that previously caused them to swell. As the peat decomposes and sinks it also becomes denser, reducing its porosity and permeability to water.

In the topmost layer of the surface peat, formed of litter from trees and other forest vegetation, water cannot easily rise through capillary forces. The hydrological properties of the surface peat layer thus changes considerably due to the impacts of drainage (Päivänen 1973), and the same is true of its chemical properties. After drainage pH levels in the peat usually decline, and concentrations of the main cations (Ca, Mg, K and Na) also decrease due to increased leaching. Mineral concentrations are likewise not replenished, since minerotrophic water is transported away by drainage ditches and no longer feeds the peatland areas between ditches.

Although drainage effectively halts peat formation, the situation is not as clear when it comes to the accumulation of carbon. Drainage generally leads to increased decomposition in older peat, but carbon fixation increases overall due to changes in the vegetation, as more carbon is taken up by the biomass of trees and dwarf shrubs etc. Even discounting the timber that will be logged, the increased biomass of tree roots has great significance in the soil carbon balance. The carbon losses caused by drainage are greatest during the first years after drainage. Over time, changes in vegetation communities reduce these losses (Laiho et al. 2003) and other factors such as declining pH in the surface peat slow decomposition (Toberman et al. 2010). In drained peatlands temperatures in the peat are generally lower than in natural peatlands, due to increased shade from trees and the insulating effect of the thicker aerated surface peat layer (Laine et al. 2004). The net impact of these differing factors and their conflicting consequences can in principle be measured by observing changes in the amounts of carbon in the peat layers, or by measuring exchanges of the gases CO_2 and CH_4 between the peatland and the atmosphere. In practice, however, it is difficult to obtain precise results on changes in carbon stocks and the carbon balance.

One way to get an overview of the overall impacts of drainage is to compare the amounts of carbon in peat layers of certain ages in drained and undrained peatlands. A comparison examining the carbon that has accumulated over the last 300 years in surface peat showed that in drained peatlands an average of 32 tonnes per hectare less carbon remains, compared to undrained peatlands (Mäkilä & Goslar 2008). This difference is due at least partly to the decomposition of older peat in drained peatlands, and the continued accumulation of new peat in undrained peatlands. If these figures for carbon loss are understood as representative at a national level, peatland drainage in Finland can be estimated to have caused a total loss of more than a hundred million tonnes of carbon from the surface peat of drained peatlands. However, the differences between the amounts of carbon in the surface peat of drained and undrained peatlands could also be related to original differences between the sites, since the peatlands chosen for drainage have typically been those with shallower peat deposits.

Several studies of the impacts of drainage on the carbon balance in surface peat have been conducted, but their results are to some extent conflicting. Minkkinen & Laine (1998) estimate that drainage increases the amount of carbon in peat by an average of 5.9 kg/m^2 over the whole of the period the peatland is drained. Their findings exhibited great variations, however, and many sites showed considerable carbon losses of up to 20 kg/m^2. The changes in the carbon stock depended on the volumes of timber and regional differences in temperatures. High carbon losses from drained peatlands have also been observed in more recent studies where peat deposits have been examined in sites that were also studied before drainage (Simola et al. 2012) or where carbon levels have been studied in peat samples from drained and undrained parts of the same peatland (Pitkänen et al. 2013). Studies of the annual balances of carbon gases indicate that net carbon loss occurs in nutrient-rich peatland types for decades after drainage, but that in drained nutrient-poor peatlands the soil acts as a carbon sink (Ojanen et al. 2013). In the peatland sites poorest in nutrients, i.e. drained raised bogs, tree stands generally do not develop, so tree litter cannot compensate for the carbon losses caused by increased decomposition. Studies generally do not account for the carbon fixation that would occur on the drained peatlands if they had been left in their natural state. The impacts of future forestry actions are also unknown, and it is possible that carbon losses from surface peat could increase due to the maintenance of drainage ditches, groundwork and fertilisation.

4.4 The impacts of restoration on peat formation

The development of peat-forming vegetation is a precondition for the formation of peat. Sphagnum mosses are of the greatest importance in this context. In areas where the peatland vegetation is dominated by sphagnum mosses it is possible to distinguish the moss growth that has developed since restoration, and the new surface peat formed from it, overlying the surface peat that formed while the peatland was still artificially drained (Figure 14).

Sphagnum moss often spread rapidly after restoration. In favourable conditions they may cover the whole surface within a few years, depending on factors such as the extent to which natural peatland plant species have survived in the site through the drainage period. Sphagnum mosses spread when their shoots branch. After sphagnum moss has spread over the surface of a peatland site it can be expected that the dying moss biomass will accumulate and form new sphagnum peat over time as it decomposes. It is almost impossible to draw a line to distinguish dead biomass (litter) and sphagnum peat; but it is possible to examine the new surface peat formed after restoration overall, including the topmost layer of living moss (Figure 14).

Observations of the accumulation of new surface peat have been made in many restored peatland sites (Tahvanainen 2006) and a comprehensive study of this issue is currently being conducted (Kareksela et al. 2013). Field surveys of the first restored peatlands, conducted ten years after restoration, revealed varying degrees of waterlogging in the peatland surfaces, with new surface peat being thicker where the water table had risen most (Tahvanainen 2006).

The accumulation of surface peat affects material flows in peatland ecosystems in many ways. The growth of peatland vegetation and the accumulation of surface peat both serve to fix carbon and nutrients. In fairly nutrient-poor pine mires in Central Finland the rates of annual carbon fixation in surface peat evidently increased to natural levels within ten years of restoration (Kareksela et al. 2013), largely due to the rapid growth of sphagnum mosses. The annual carbon fixation rate in new surface peat averaged about 108 g/m^2 over the first ten years. For a total restored area of 15,000 hectares of peatland the carbon fixed in this way would be the equivalent of almost 60,000 tonnes of carbon dioxide. Peatland restoration also affects the leaching of organic carbon and emissions of methane from peatlands. This could affect the climate impact of restoration even more than the sink effect of carbon fixation in surface peat (Info box 3).

In addition to impacting the carbon cycle, restoration also affects the chemical characteristics of the surface peat. Concentrations of Ca, K, Mg, Mn and P have been observed as rising back to levels observed in similar natural peatlands within about ten years of restoration (Haapalehto et al. 2010). In natural undrained peatlands these elements exhibit typical distribution patterns in peat layers at different depths (Damman 1978, Pakarinen 1978). Since the nutrients released from litter and root exudates are recycled by the living parts of peatland plants, the concentrations of many nutrients are highest in the uppermost part of the peat layer. This kind of natural depth distribution has been observed as returning, at least with respect to K and Mn concentrations, within ten years of restoration (Haapalehto et al. 2010). Such findings indicate that the nutrient cycle between plants and peat has become normalised.

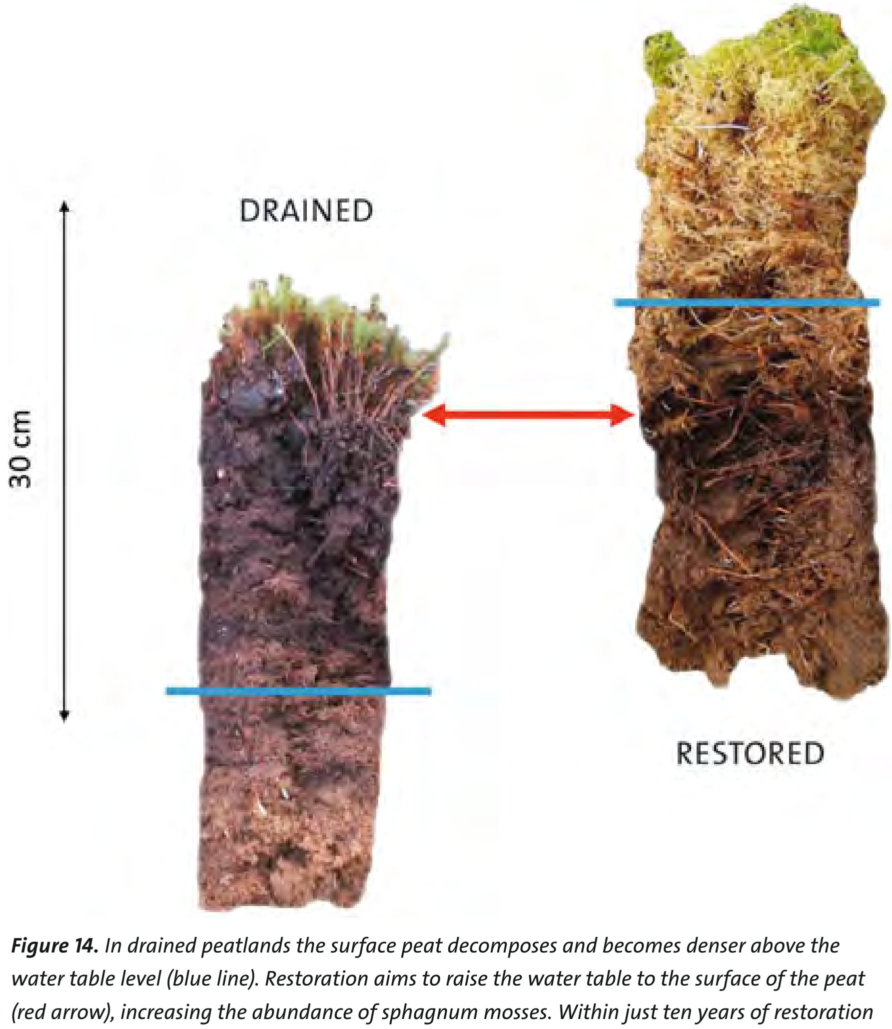


Figure 14. *In drained peatlands the surface peat decomposes and becomes denser above the water table level (blue line). Restoration aims to raise the water table to the surface of the peat (red arrow), increasing the abundance of sphagnum mosses. Within just ten years of restoration the sphagnum mosses may start to form new sphagnum peat, which will gradually accumulate in layers beneath the water table in relatively anoxic conditions. Both of these peat sections have as their lowest layer pale brown sphagnum peat that formed when the peatland was in its natural state. Even after restoration the impacts of the drained peatland forest stage can be seen as a darker layer between the pre-drainage and post-restoration sphagnum peat layers, containing remnants of pine needles, bark, cones, and forest mosses.* PHOTOS: TEEMU TAHVANAINEN.